Monitoring Biological Heterogeneity in a Northern Mixed Prairie Using Hierarchical Remote Sensing Methods

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ABSTRACT

Heterogeneity, the degree of dissimilarity, is one of the most important and widely applicable concepts in ecology. It is highly related to ecosystem conditions and features wildlife habitat. Grasslands have been described as inherently heterogeneous because their composition and productivity are highly variable across multiple scales. Therefore, biological heterogeneity can be an indicator of ecosystem health. The mixed prairie in Canada, characterized by its semiarid environment, sparse canopy, and plant litter, offers a challenging region for environmental research using remote sensing techniques. This thesis dwells with the plant canopy heterogeneity of the mixed prairie ecosystem in the Grasslands National Park (GNP) and surrounding pastures by combining field biological parameters (e.g., grass cover, leaf area index, and biomass), field collected hyperspectral data, and hierarchical resolution satellite imagery. The thesis scrutinized four aspects of heterogeneity study: the importance of scale in grassland research, relationships between biological parameters and remotely collected data, methodology of measuring biological heterogeneity, and the influence of climatic variation on grasslands biological heterogeneity. First, the importance of scale is examined by applying the semivariogram analysis on field collected hyperspectral and biophysical data. Results indicate that 15 - 20 m should be the appropriate resolution when variations of biological parameters and canopy reflectance are sampled. Therefore, it is reasonable to use RADARSAT-1, Landsat TM, and SPOT images, whose resolutions are around 20 m, to assess the variation of biological heterogeneity. Second, the efficiency of vegetation indices derived from SPOT 4 and Landsat 5 TM images in monitoring the northern mixed prairie health was examined using Pearson's correlation and stepwise regression analyses. Results show that the spectral curve of the grass canopy is similar to that of the bare soil with lower reflectance at each band. Therefore, vegetation indices are not necessarily better than reflectance at green and red wavelength regions in extracting biological information. Two new indices, combining reflectance from red and mid infrared wavelength regions, are proposed to measure biological parameters in the northern mixed prairie. Third, texture analysis was applied to quantify the biological variation in the grasslands. The textural parameters of RADARSAT imagery correlated highly with standard deviation of the field collected canopy parameters. Therefore, textural parameters can be applied to study the variations within the mixed prairie. Finally, the impacts of climatic variation on grassland heterogeneity at a long time scale were evaluated using Advanced Very High Resolution Radiometer (AVHRR) , Normalized Difference Vegetation Index (NDVI), Maximum Value Composite (MVC), and SPOT Vegetation NDVI MVC imagery from 1993 to 2004. A drought index based on precipitation data was used to represent soil moisture for the study area. It was found that changes of temperature and precipitation explain about 50% of the variation in AVHRR NDVI (i.e., temporal heterogeneity) of the northern mixed prairie. Trend line analysis indicates that the removal of grazing cattle carry multiple influences such as decreasing NDVI in some parts of the upland and valley grassland and increasing NDVI in the valley grassland. Results from this thesis are relevant for park management by adjusting grassland management strategies and monitoring the changes in community sizes. The other output of the thesis is furthering the remote sensing investigation of the mixed prairie based on information of the most appropriate resolution imagery.

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CHAPTER 1 - INTRODUCTION

1.1 Research Background

1.1.1 Heterogeneity and grassland

The term "heterogeneity" has received more and more attention in ecology since 1970s when researchers began to question the homogeneous hypothesis of the ecological environment (McIntosh 1991). Thereafter, it became a widely adopted concept in ecology and related areas. At first glance, heterogeneity has a very clear meaning (Kolasa and Rollo 1991); it is the antonym of homogeneity. Homogeneity describes the condition of unity; on the contrary, heterogeneity describes variation. However, it is not easy to define heterogeneity because it has different meanings when viewed from different perspectives (Kolasa and Rollo 1991). While Seixas (2000) pointed out that heterogeneity is the variation restricted in a defined spatial area based on pattern and processes, Collins (1992) indicated that heterogeneity, from a statistical point of view, measures the degree of dissimilarity. As a result, Kolasa and Rollo (1991), the editors of the first book discussing ecological heterogeneity, didn't even define heterogeneity. However, most authors agreed that heterogeneity is related to the extent of diversity (Peet 1974, Krebs 1989, Cousins 1991, Dutilleul and Legendre 1993, Li and Reynolds 1995, Adler *et al.* 2001) and can be interpreted and measured as pattern (Dutilleul and Legendre 1993, Li and Reynolds 1995) and variation (Kolasa and Rollo 1991, Li and Reynolds 1995, Seixas 2000).

It has been broadly accepted that heterogeneity has at least two dimensions, spatial heterogeneity and temporal heterogeneity (Kolasa and Rollo 1991). Spatial heterogeneity means spatial variability or spatial pattern (Adler *et al.*, 2001). “Spatial heterogeneity within ecosystems and among ecosystems” is critical to the functioning of individual ecosystems and of entire landscapes (Kronert *et al.* 2001). Temporal heterogeneity is similar to spatial heterogeneity except that it describes the variations of heterogeneity over time (Kolasa and Rollo 1991). The relationship between temporal heterogeneity and spatial heterogeneity is complex (Kolasa and Rollo 1991), different temporal heterogeneity of neighboring sites is spatial heterogeneity.

Grasslands are inherently heterogeneous because their composition, productivity, and diversity are highly variable across multiple scales (Ludwig and Tongway 1995). A higher degree of heterogeneity in ecological systems is supposed to associate with higher ecosystem stability (Tilman and Downing 1994). Ecosystem properties (Li and Reynolds 1995), such as biomass or species composition, can be treated as the objectives of a heterogeneity study. Spatially, heterogeneity can be measured as the variation of characteristics of grass canopy, such as percent cover, species composition, biomass, etc., across space. Temporally, it can be measured as the change of grass production or other canopy characteristics over time.

1.1.2 Methods of grassland heterogeneity measurement

Generally, methods of heterogeneity measurement can be divided into three groups: direct measurement of heterogeneity based on fieldwork, indirect measurement of heterogeneity purely supported by remotely sensed data, and a hybrid method combining field work and remote sensing techniques.

Methods of Direct Measurement

To date, many methods have been proposed to calculate heterogeneity quantitatively based on field collected biological parameters. These methods can be categorized into three main groups according to characteristics of distribution (Armesto et al. 1991, Dutilleul and Legendre 1993, Li and Reynolds 1995). The first group uses indices to measure heterogeneity based on plot or site data. Frequently used indices include Simpson's index, the Shannon-wiener function, and richness and evenness indices (Krebs 1989, Southwood and Henderson 2000). However, these indices can be only applied on data without spatial reference and they are unable to differentiate between species (Cousins 1992). Methods in the second group deal with point pattern data. Parameter k of negative binomial, nearest neighbor index, and block-size variance statistics are among the commonly used methods (Li and Reynolds 1995). The third group treats surface pattern data. Fractal dimensions, semivariograms, correlograms, and autocorrelation indices are used to quantify heterogeneity (Dutilleul and Legendre 1993, Li and Reynolds 1995). However, traditional fieldwork is time consuming, costly, and almost impossible if tasks of heterogeneity assessment are across a large area and a long time span.

Indirect Grassland Heterogeneity Measurement – Environment Remote Sensing

Satellite remote sensing, which collects radiative data of ground objects at different spatial and temporal resolutions, might have the potential to be a powerful tool in evaluating grassland heterogeneity. Currently available methods to estimate the green vegetation cover and biomass from remotely sensed data can be grouped into three basic approaches: spectral mixture models, calibrated cover-radiance relationships, and vegetation indices approaches (Purevdorj et al., 1998).

Spectral Mixture Modeling

Mixture modeling includes two type of modeling, linear and nonlinear (Schowengerdt 1997). Linear mixture modeling assumes that each field within a ground pixel contributes an amount characteristic of the cover type in that field to the signal received at the satellite sensor and is proportional to the area of the cover type. The main problem in using linear mixture modeling for grasslands is the location of pure end member for the green cover component, because vegetation density in grassland is relatively low (Purevdorj et al. 1998). Nonlinear mixing occurs when radiation transmission through one material and second reflectance occurs from other materials, or there are multiple reflections within or between materials (Schowengerdt 1997). A nonlinear mixing model was generated to deal with this situation. Nonlinear models are more accurate in some circumstances, but certain nonlinear curves or forms should be learned before application (Kimes and Nelson 1998).

Cover-radiance Relationships

The Cover-radiance relationship approach investigates the relationship between field collected canopy cover data and radiance data. They are best suited to medium spatial resolution satellite sensor data, such as Landsat TM, MSS, and SPOT since they require accurate measurement of vegetation cover on the ground covering the same area. This method was used in many studies (Ferro 1998, Lewis 1994, Schmidt and Karnieli 2002, Todd and Hoffer 1998, Wang et al. 2002). Problems with comparing satellite data and ground measurement include the accuracy of estimating a large area and the efficiency of the model for describing the canopy condition (Purevdorj et al. 1998).

Vegetation Indices

Soil and green vegetation have different modes of reflectance characteristics. The mixture of soil, green vegetation, and shade in the pixels make remote sensing of grassland a challenge (Perry and Lautenschlager 1984, Todd and Hoffer 1998). Vegetation indices were produced to minimize the impacts of soil background and senescent materials (Jenson 2006). Red and near infrared have been found to be good at detecting green vegetation (Purevdorj et al. 1998). Therefore most vegetation indices make use of the red and near infrared portion of spectral reflectance. They have been shown to be well correlated with vegetation parameters such as leaf area index (LAI), biomass, canopy cover, and the fraction of absorbed photosynthetically active radiation (*f*APAR) (Gao et al. 2000, Jenson 2006).

The selection and suitability of a vegetation indices is generally determined by its sensitivity to the characteristics of interest (Gao et al. 2000, Perry and Lautenschlager 1984, Schmidt and Karnieli 2002, Weiser et al. 1986). Many efforts have been made to optimize vegetation indices that make them insensitive to variations in sun-surface-sensor geometries, atmosphere, calibration, and canopy background (Gao 2000). Frequently used vegetation indices include Simple Ratio (SR), Normalized Difference Vegetation Index (NDVI), Soil-Adjusted Vegetation Index (SAVI), Enhanced Vegetation Index (EVI), Green Vegetation Index (GVI), and Transformed Soil Adjusted Vegetation Index (TSAVI) (Chen 1996, Todd and Hoffer 1998).

Remote sensing of grassland biological heterogeneity

Remote sensing techniques evaluate grassland heterogeneity by measuring the variation of spectral reflectance from vegetation canopy. Therefore, they can be considered as indirect ways to assess heterogeneity. Briggs and Nellis (1991) applied textural analysis to evaluate the heterogeneity by measuring the seasonal variation of biomass. Their work might be the first case of a grassland heterogeneity study supported purely by remotely sensed data. Riera et al. (1998) used the standard deviation of the Normalized Difference Vegetation Index (NDVI) to indicate Northern American landscape heterogeneity. Other studies have also investigated the variation of biological parameters and biomass over space and time (e.g. Henebry 1997, Fuller 1998, Mino *et al.* 1998, Milich and Weiss 2000, Wang *et al.* 2003). However, these results might be questionable without the support of field collected information.

Hybrid Method

There are close relationships between field biological data and spectral data (Weiser *et al.* 1986, Lewis 1994). It is reasonable to hypothesize that there are high correlations between variation of field - collected biological variables of vegetation canopy and spectral variation. There have been a few work observing grassland heterogeneity by utilizing remotely collected data and field data (e.g. Jorgensen and Nohr 1996, Lauver 1997, Gould 2000, Zhang *et al.* 2005). Imagery measured variations were used to detect species diversity and standard deviation of biological variables.

1.2 Research Objectives

1.2.1 Research gap

Though remote sensing has long been used on other grassland ecosystems, e.g. studies in tallgrass prairie (e.g., Asrar *et al.* 1986, Asrar *et al*. 1989, Guo *et al.* 2005), shortgrass prairie (e.g. Lauver 1997), and other grasslands in semiarid and arid environments (e.g., Wilson 1989, Lewis 1994, Dilley *et al.* 2004), remote sensing applications in the northern mixed prairie are challenging because of this ecosystem's high amount of non-photosynthetic materials and low to medium green vegetation cover. To date, only a few studies have been conducted in the mixed prairie (e.g. Hill *et al.* 2000, Davidson and Csillag 2001, Mitchell and Csillag 2001). Neither spatial heterogeneity nor temporal heterogeneity in the northern mixed prairie has been thoroughly examined. Further work is needed to solve the current research gap of grassland heterogeneity measurement. A methodology is still needed to assess the representation of grassland heterogeneity with remotely sensed data by combining field collected biological and remotely sensed data.

1.2.2 Hypotheses

The overall hypothesis of this study is that grassland heterogeneity can be used as an indicator of the condition of the grassland ecosystem and that it can be measured by using remote sensing techniques.

More specifically,

(1) The measurement of heterogeneity is scale dependent. Certain scales are more appropriate for measuring heterogeneity than others. Appropriate resolutions should be chosen when dealing with grassland heterogeneity;

(2) The northern mixed prairie is spectrally specific. However, it is still possible to monitor the biological variations within the mixed prairie ecosystem using remote sensing techniques;

(3) Certain spectral vegetation indices are better than others at extracting biological information for the northern mixed prairie;

(4) Parameters from texture analysis will be efficient in measuring grassland heterogeneity;

(5) High temporal and low spatial resolution imagery will be effective at temporal heterogeneity measurement. The variation can be evaluated through measuring NDVI.

1.2.3 Goals

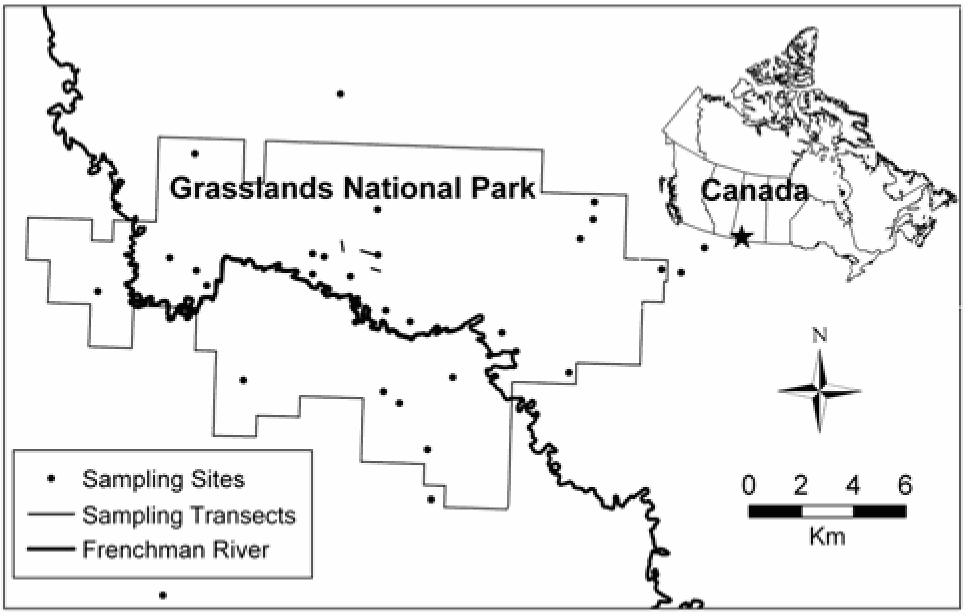
As a comprehensive study to measure the grassland heterogeneity using remotely sensed data, this study aims to:

- Identify the spatial variations for different biological variables and investigate the usefulness of spectral vegetation indices for grassland heterogeneity measurement;
- Develop an efficient method for measuring grassland heterogeneity;

- Evaluate the potential of RADARSAT and texture analysis on grassland heterogeneity monitoring; and
- Assess the change of NDVI (representative of NPP) in the park area after the removal of grazing cattle using historical remotely sensed imagery.

1.3 Study Area

The study area is the west block of Grasslands National Park (GNP) (49° N, 107° W) and surrounding pastures, located in southern Saskatchewan along the Canada - United States border. This area falls within the mixed prairie ecosystem (Figure 1.1) (Coupland 1992). The park is approximately 906 km^2 in area, consisting of two discontinuous blocks, west and east. The first land was acquired for the park in 1984; hence, most areas of the park have been under protection from livestock grazing for over 20 years. The park area consists of upland and valley grasslands (Figure 1.2). The dominant plant community in the uplands of the mixed grass prairie ecosystem is needle-and-thread – blue grama grass (*Stipa-Bouteloua*), which covers nearly two thirds of the park's ground area. The dominant species in this community include needle-and-thread (*Stipa comata Trin. & Rupr*), blue grama grass (*Bouteloua gracilis (HBK) Lang. ex Steud.*), and western wheatgrass (*Agropyron smithii Rydb.*) (Fargey *et al*. 2000). Comparatively, valley grasslands are dominated by western wheatgrass and northern wheatgrass (*Agropyron dasystachym*), along with higher densities of shrubs and occasional trees. The GNP area has a mean annual temperature of 3.8 ºC and a total annual precipitation of 325mm (Environment Canada 2003); approximately half of the precipitation is received as rain during the growing season. Common soils in the Park areas are chernozemic soils and solonetzic soils (Fargey *et al*. 2000). Chernozemic soils are the most common in grassland communities, with a dark color and high amount of organic content. Solonetzic soils, with their high salinity and lighter color, are formed due to the drought and high evaporation (Michalsky *et al.* 1994). Under the sparse vegetation canopy in the Park area, a large portion of the surface is covered by microphytic communities of small non-vascular plants. These microphytic communities include mainly mosses, lichens and fungi, which form biological crusts over soils and rocks.



(a)

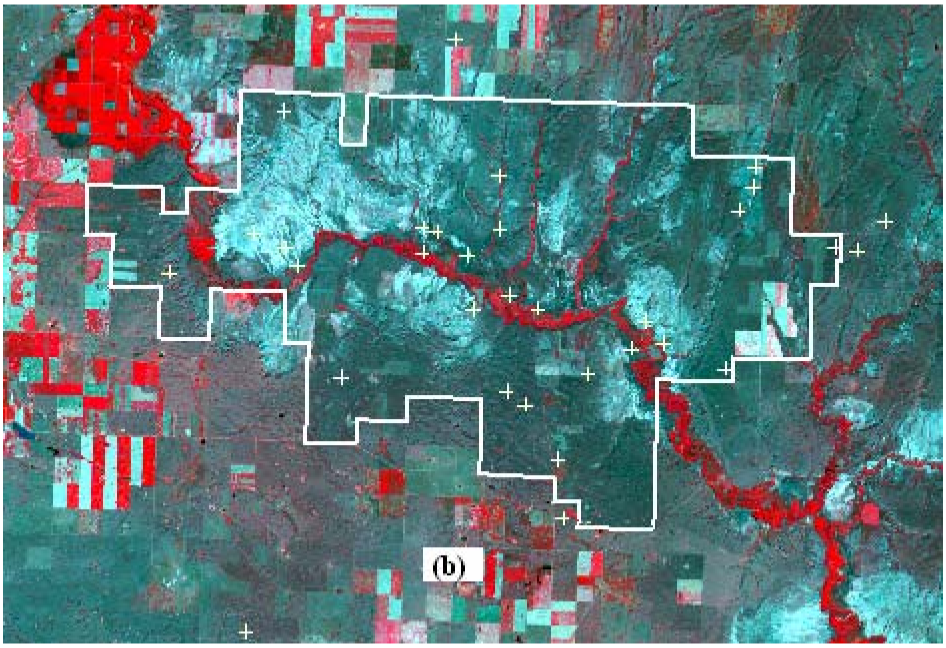


Figure 1.1 The study area, west block of Grasslands National Park (GNP) (a) and a false color composite of SPOT 4 image taken on June 22, 2005 (b). Field sampling locations are displayed as points (a) and crosses (b).

1.4 Thesis Structure

A hybrid method is applied to study biological heterogeneity (Figure 1.3): The whole thesis is based on satellite imagery with hierarchical spatial resolutions [SPOT 4, Landsat TM, RADARSAT-1, AVHRR Normalized Difference Vegetation Index (NDVI) Maximum Value Composite (MVC), and SPOT Vegetation NDVI MVC] and coupled field work (biological and ground-collected hyperspectral data). Climatic data and environment factors − such as precipitation, temperature, organic contents, soil moisture, and slope − were also used to explain the spatial and temporal variation. The heterogeneity study is divided into four components; the scale of variation in the northern mixed prairie and the most appropriate

Figure 1. 2 A typical landscape of the northern mixed prairie from upland to valley grassland. Please note that there are large amounts of dead materials in the sparse grass canopy, as shown in the foreground of the picture. The dominant plant community in the uplands of the mixed grass prairie ecosystem is needle-and-thread – blue grama grass. Valley grasslands are dominated by western wheatgrass and northern wheatgrass. Green vegetation canopy with a linear shape in the valley is mainly dominated by shrub communities.

resolution for measuring grassland heterogeneity, the efficiency of applying vegetation indices in monitoring grassland ecosystem, the methodology of spatial heterogeneity measurement, and the temporal change of the northern mixed prairie and their relationships with climatic variation. Consequently, there are six chapters in this thesis. The first chapter is the introduction, which includes a brief review of heterogeneity studies and structure of the whole thesis. The second chapter applied ground collected hyperspectral data to study the influences of scale on heterogeneity measurements, where vegetation indices and semivariogram analyses were used to study the scale of variation. The third chapter discusses the possibility of applying broadband satellite remote sensing to monitor the northern mixed prairie health. Comparisons were made between traditional vegetation indices and two new indices in extracting biological variables. The fourth chapter applies textural parameters, such as entropy and contrast, to RADARSAT imagery to extract ground biological heterogeneity information. The fifth chapter uses AVHRR NDVI MVC, SPOT Vegetation MVC, and climatic data to explore influences of climatic variation on temporal heterogeneity. The sixth chapter is the summary of the thesis.

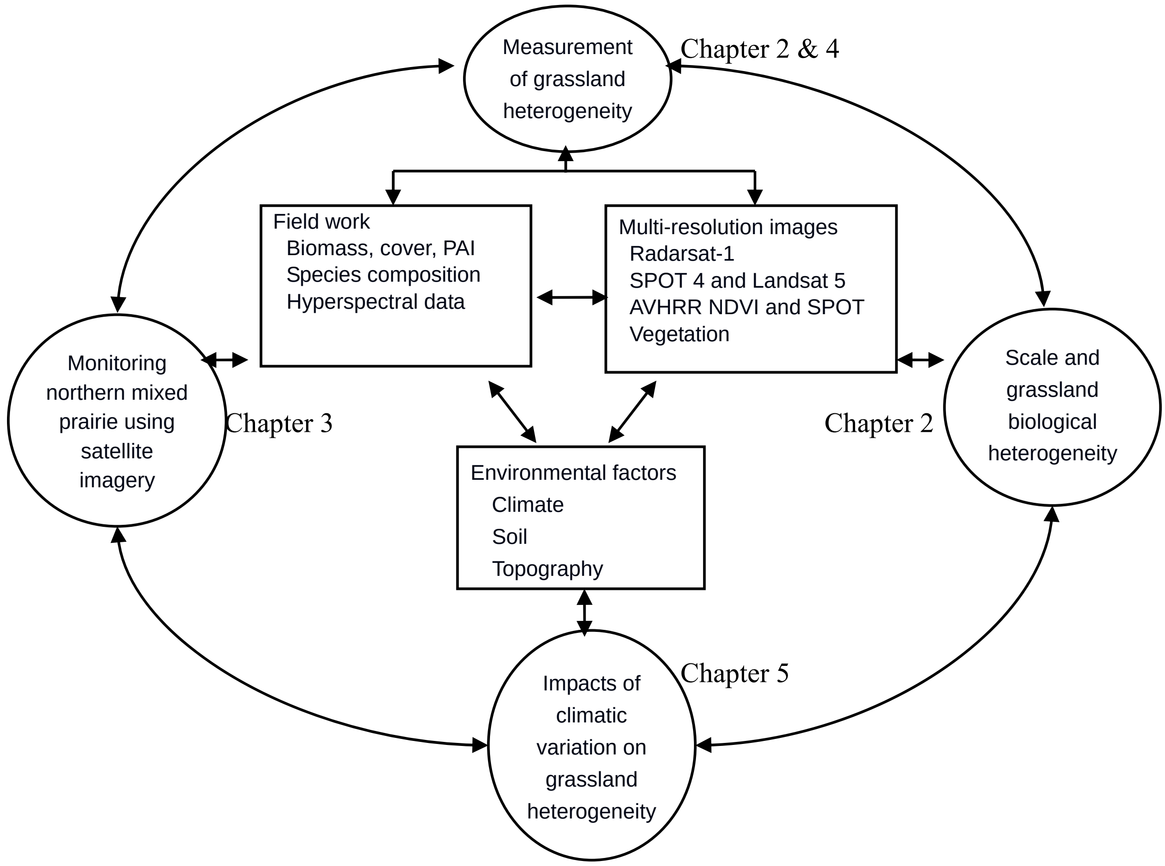


Figure 1.3 Methodology framework of this thesis with each ellipse stands for one chapter.

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CHAPTER 2 - MEASURING BIOLOGICAL HETEROGENEITY IN THE NORTHERN MIXED PRAIRIE AT THE COMMUNITY LEVEL

2.1 Abstract

Biological heterogeneity, defined as the degree of dissimilarity between biological parameters (e.g., biomass, green vegetation, and Plant Area Index (PAI)), is one of the most important and widely applicable concepts in ecology, due to its close link with biodiversity. To investigate grassland biological heterogeneity, three transects extending from upland to valley grasslands were selected at Grasslands National Park (GNP), Canada, representing the northern mixed prairie. For the purposes of analysis, three types of data were collected: remote sensing close range hyperspectral data, biological data (PAI, biomass, and vegetation cover), and environmental data (soil moisture, organic content, and bulk density). Methodologically, field-level remote sensing data were used to calculate spectral vegetation indices. These indices (plus the biological parameters detailed above) were then used in regression analyses, with a goal of assessing the feasibility of using remote sensing data to study biological heterogeneity. The results of the regression analysis indicate that it is feasible to use ground-level remote sensing data to represent biological parameters. These indices can explain about 40% – 60% of the biological variation. Semivariogram analyses were further applied on these data to investigate their range of spatial variation. Spatial variations in the mixed prairie for PAI, total biomass, green cover, and spectral vegetation indices have ranges from 31 m to 120 m, with the majority occurring around 50 to 60 m. Therefore, the most

appropriate spatial resolution for detecting variation from upland to valley grasslands is 10 - 20 m.

Key words: Biological heterogeneity, semivariogram, hyperspectral, Grasslands National Park

2.2 Introduction

As a pool of carbon dioxide and a variegated gene pool for both wild life and vegetation, the mixed prairie of North America is a vital component of the global ecosystem (Coupland 1992). The grassland has been described as inherently heterogeneous because its composition, productivity, and diversity are highly variable across multiple scales (Ludwig and Tongway 1995). Biological heterogeneity, defined as the degree of dissimilarity of biological parameters (e.g., biomass, green vegetation, and Plant Area Index (PAI)), is an important indicator of ecosystem conditions (Peet 1974, West 1993, Southwood and Henderson 2000). Specifically, degradation of grasslands results in a decreased spatial scale of variation due to the fragmentation of plant communities, with a resultant (and perceptible) change in the area's biological parameters. Therefore, the successive monitoring of biological heterogeneity provides clues to changes in grasslands ecosystem conditions.

Satellite remote sensing (using the reflectance data of ground objects at different spatial resolutions) has been applied to the study of landscape heterogeneity and species richness (Jorgensen and Nohr 1996, Lauver 1997, Gould, 2000). However, before such a study can be performed, an appropriate image resolution must be chosen, since the ability to detect heterogeneity is highly related to the appropriateness of the resolution selected. Furthermore, the distinct characteristics of the northern mixed prairie (e.g., low biomass vegetation, high soil exposure, and large amount of senescent materials) make the application of broadband satellite remote sensing especially challenging, since these conditions diminish the correlation between biological parameters, reflectance, and vegetation indices. Fortunately, hyperspectral remote sensing, with numerous bands and greatly improved spectral resolution, has demonstrated its ability for more accurately predicting biological measurements and distinguishing spectrally-specific materials (Mutanga and Skidmore 2003). Previous work has shown that it is possible to use proximal hyperspectral remote sensing techniques to scrutinize the spatial variation in a grassland environment (e.g., Mutanga *et al.* 2004).

There are at least three methods available for detecting spatial variation using field-collected hyperspectral transect data: coefficient of variance (CV), wavelet transform (WT), and semivariogram (Figure 2.1). CV can be used to find the images or bands that are best able to detect heterogeneity and variation. Roth (1976) and Wiens (1974) applied CV as an index for measuring the spatial heterogeneity of grasslands with field data. WT, a signal processing tool that provides a means for analyzing signals at various scales, has also been applied to detect the spatial scale of a cropland (Si and Farrell 2004). Finally, semivariogram, a function that describes the relationship between semivariance and lag distance (or sample interval), can be used to decide the most appropriate scale for remote sensing studies (Curran 1988, Woodcock *et al.* 1988). Among these three methods, semivariogram is most commonly applied to the study of spatial variation scales, due primarily to its ability to capture spatial structure (Curran 1988, Treitz and Howarth 2000). Directional semivariogram has shown potential in predicting the structural parameters of a coniferous forest stand (St-Onge and Cavayas 1995). This technique also has other documented applications in the forestry sector, including a study of the scales of different forest types using transects from images (Treitz and Howarth 2000, Treitz 2001). Application of semivariogram analysis to hyperpspectral field data allowed Rahman *et al.* (2003) to propose the minimum resolution necessary for classifying southern California chaparral and grassland. However, the parameters of the semivariogram in their studies were obtained either from visual fitting, which is not theoretically strict, or by applying the least squares method to the empirical variogram. The results of this method are also not reliable because the same dataset can produce several different empirical variograms from different realizations (Diggle, *et al.* 2003). Finally, the biological implications of their results are not very clear because there were insufficient supporting field data.

In response to these issues, the objective of the present study is to conduct a comprehensive exploration of remote sensing applications focusing on spatial variations of a northern mixed prairie. Specifically, this study will 1) evaluate the influence of spatial scale on grassland biological parameters and vegetation indices; 2) investigate the relationships between scales derived from biological parameters, environmental factors, and vegetation indices; and 3) determine the most suitable resolution for studies in the northern mixed prairie.

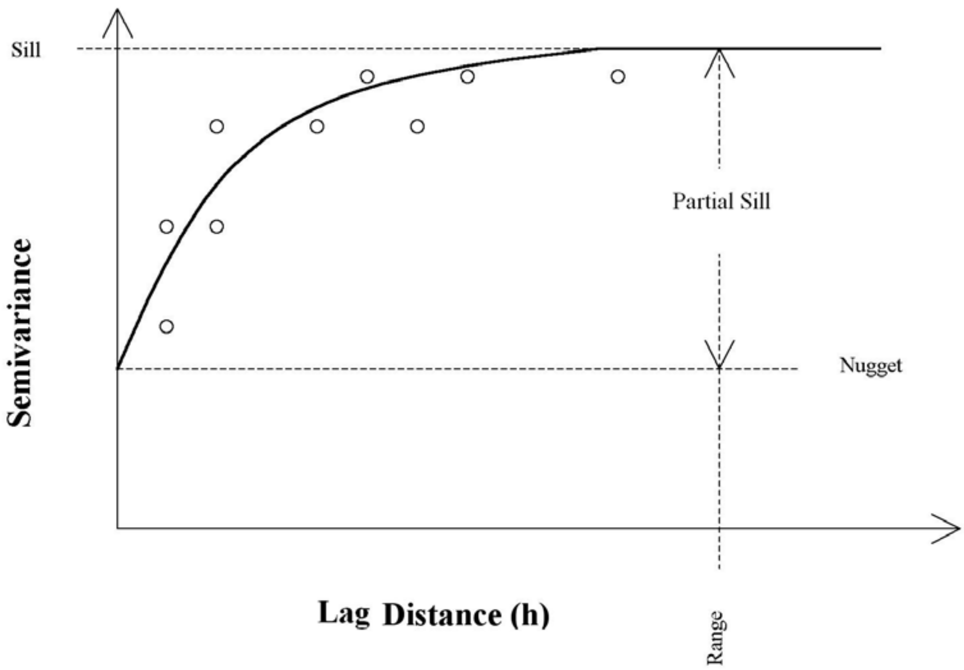


Figure 2.1 A typical spherical model of semivariogram. Nugget, sill, and range are three components of a semivariogram. Semivariance is a measurement of variation for spatial feature with different lag distance (h) and sill is the largest semivariance value between spatial features. Partial sill is the different between sill and nugget and is part of the semivariance due to autocorrelation. While range indicates the scale of spatial autocorrelation, nugget generally corresponds to measurement errors or noise. Circles in the graph indicate empirical semivariogram.

2.3 Study Area

The selected study area is inside the Grasslands National Park (GNP) (49° N, 107° W), located in southern Saskatchewan along the Canada - United States border. The area falls within the mixed prairie ecosystem (Coupland 1992). The park is approximately 906 km^2 in area, consisting of two discontinuous blocks, west and east. As the land was first acquired for the park in 1984, some areas of the park have been under protection from livestock grazing for over 20 years. The park area consists of upland, sloped, and valley grasslands. The dominant plant community in the uplands is needle-and-thread – blue grama grass (*Stipa-Bouteloua*), which covers nearly two thirds of the park's ground area. Dominant grass species in this community include needle-and-thread (*Stipa comata Trin. & Rupr.*), blue grama grass (*Bouteloua gracilis (HBK*) *Lang. ex Steud*.), and western wheatgrass (*Agropyron smithii Rydb.*). Comparatively, valley grasslands are dominated by western wheatgrass *a*nd northern wheatgrass (*Agropyron dasystachym*), along with higher densities of shrubs and occasional trees. As transitional areas between upland and valley grasslands, the sloped grasslands have more grass species. There are various growing season lengths for different vegetation species. For native grass, the growing season lasts about 2 to 3 months, generally from late May to early August. However, the growing season for some shrub species (e.g. silver sagebrush (*Artemisia cana*)) may range from mid-April to late October. The area's monthly mean daily temperature ranges from -12.4 ºC in January to 18.3 ºC in July and the total annual precipitation is 325 mm, where approximately half of the precipitation is received as rain during the growing season (Environment Canada 2003).

2.4 Methods

2.4.1 Field data collection and processing

Three transects, crossing through three communities (e.g., *Stipa comata – Bouteloua gracilis* for upland grasslands, *Artemesia frigida - Stipa comata - Bouteloua gracilis* for sloped grasslands, and *Artemesia sp. – Agropyron smithii* for valley grasslands), were selected using a stratified random design. Accessibility is also a factor in sites selection. The lengths of these three transects were 350, 400, and 500 m respectively. Quadrats (50 x 50 cm) were placed every 10 m along the transects. The cover percentages of grass, forb, shrub, litter, moss, lichen, bare ground, and standing dead grass, as well as species composition, were collected at each quadrat. Percent cover was estimated to the nearest 5% for values ranging from 20% to 90% and to the nearest 1% for values less than 20% and greater than 90%. Biomass was collected at the same time but using a 20 x 50 cm quadrat due to a park restriction. This clipped fresh biomass was sorted into four groups: grass, forb, shrub, and dead materials. It was then dried in an oven for 48 hours at 60℃. PAI was measured using a LiCor-LAI-2000 Plant Canopy Analyzer (Li-Cor, Inc., Lincoln, Nebraska). One soil core was collected from each quadrat at a depth of 15 cm with a soil probe. Collected soil cores were put in sealed plastic bags to retain the soil moisture. Fifteen grams of soil samples for each quadrat were dried in the oven at 105 ℃ for 8 hours to measure soil moisture. Five grams of sample for each quadrat was put into a furnace at 840℃ for 40 minutes to determine its organic content (Wang and Anderson 1998). Samples used to measure organic content were air-dried and ground before being placed into the furnace. Bulk density was calculated based on measured soil moisture and the soil core volume (Blake and Hartge 1986).

2.4.2 Remote sensing data collection and preprocessing

Canopy reflectance was measured using an ASD FR Pro spectroradiometer (Analytical

Spectral Devices, Inc., USA) for each quadrat. The measurement range was 350-2500nm, and the spectral resolution was 3 nm from 350 to 1000 nm and 10 nm from 1000 to 2500 nm. The 25^{o} field of view probe was pointed down vertically, giving a nadir view of the canopy from a height of approximately 1 meter. Measurements were taken between 1000h and 1400h local time on clear days. A white reflectance panel (Labsphere, USA) was used to calibrate the reflectance at approximately 10 minute intervals to minimize the influence of atmospheric condition changes.

Normalized Difference Vegetation Index (NDVI), Renormalized Difference Vegetation Index (RDVI), ND680, ND705, and Normalized Difference Water Index (NDWI) (Table 2.1) were calculated based on their high correlation with biological parameters and biological meaning. NDVI exploits the contrasting reflectance between red and near-infrared regions and is commonly used to extract canopy information (Rouse *et al.* 1974). RDVI was developed to linearize the relationship between vegetation and surface parameters, as the correspondence between vegetation indices and biological parameters is not necessarily linear (Chen 1996). NDVI and RDVI are simulated vegetation indices because they were calculated by averaging the reflectance of the spectraradiometer's narrow bands to the corresponding broad bands in Landsat Thematic Mapper imagery. Two narrow band vegetation indices, ND680 and ND705, are good at measuring chlorophyll absorption, which makes them useful for representing the green portion of the canopy (Blackburn 1998, Sims and Gamon 2002). NDWI is highly correlated with canopy water content (Hardisky *et al.*, 1983; Jensen, 2006).

2.4.3 Statistical analysis

First, the variation of species composition along transects, based on species presence or absence, was examined using Detrended Correspondence Analysis (DCA) with PC-ORD (MjM Software, USA). DCA compares differences among plant communities along the transects (McCune and Grace 2002). Before applying DCA, all data were pooled together and data were averaged for every five quadrats (i.e., over 50 m) in each transect to better represent different communities. Second, the relationships between single biological parameters and vegetation indices were highlighted by Pearson correlation. With all data from three transects pooled together, stepwise regression was then applied to determine the relationships between biological parameters and spectral vegetation indices. These results were validated using the Jack-Knife cross validation method, which withdraws one sample each iteration and runs the model through n-1 iterations. Finally, data from all three transects were pooled together to create an average scale (Woodcock *et al.* 1988). The scale of variation was estimated using the semivariogram approach, where range indicates the distance within which spatial autocorrelations occur. Empirical variograms were first computed to estimate the preliminary values for partial sill, range, and nugget. Then, a maximized likelihood estimation or restricted maximized likelihood was applied to the original dataset in order to estimate covariate parameters. Trends were carefully inspected and removed for nonstationary data to check variations at a small scale. As all the empirical variograms resembled an exponential model upon visual inspection, an exponential model was used as a representation of the correlation function in the maximum likelihood estimation.

The whole process was completed using R and geoR (Ribeiro and Diggle 2001).

Table 2.1 Vegetation indices selected for this study

Vegetation index	Equation	Reference
NDVI	$\frac{TM4-TM3}{TM4+TM3}$	Rouse *et al.*, 1973
RDVI	$\frac{TM4-TM3}{\sqrt{TM4+TM3}}$	Reujean and Breon, 1995
ND680	$\frac{R800-R680}{R800+R680}$	Blackburn, 1998
ND705	$\frac{R750-R705}{R750+R705}$	Sims and Gamon, 2002
NDWI	$\frac{TM4-TM5}{TM4+TM5}$	Hardisky *et al.*, 1983

Note: TM4 and TM3 stand for the reflectance values in near-infrared and red bands for simulated Landsat TM images. R stands for the field collected hyperspectral band.

2.5 Results

2.5.1 Species variation and environmental parameters

It is possible to separate quadrats into two large groups: communities in upland and sloped grassland dominated by needle-and-thread; and communities in valley grassland (or in depressions) dominated by western wheatgrass (Figure 2.2). Differences between these two groups mainly exist in the soil water, topography, and soil characteristics. Needle-and-thread dominates in dry upland soils and is rare in clay soils. Western wheatgrass and northern wheatgrass are rhizomatous and mostly flourish in clay and clay loam soils in valley grasslands. Compared with the widely spread *Stipa* community, the *Agropyron* community is clustered. There are also two other smaller groups, each dominated by western snowberry (*Symphoricarpos occidentalis*) and silver sagebrush, as shown in Figure 2.2. It is hard to separate sloped grasslands from upland grasslands because they are similar in species composition. Environmental factors (soil moisture and organic content) have correlation coefficients of 0.6 and 0.56 respectively with the first axis (mainly the variation of species composition), which indicates their importance in vegetation growth.

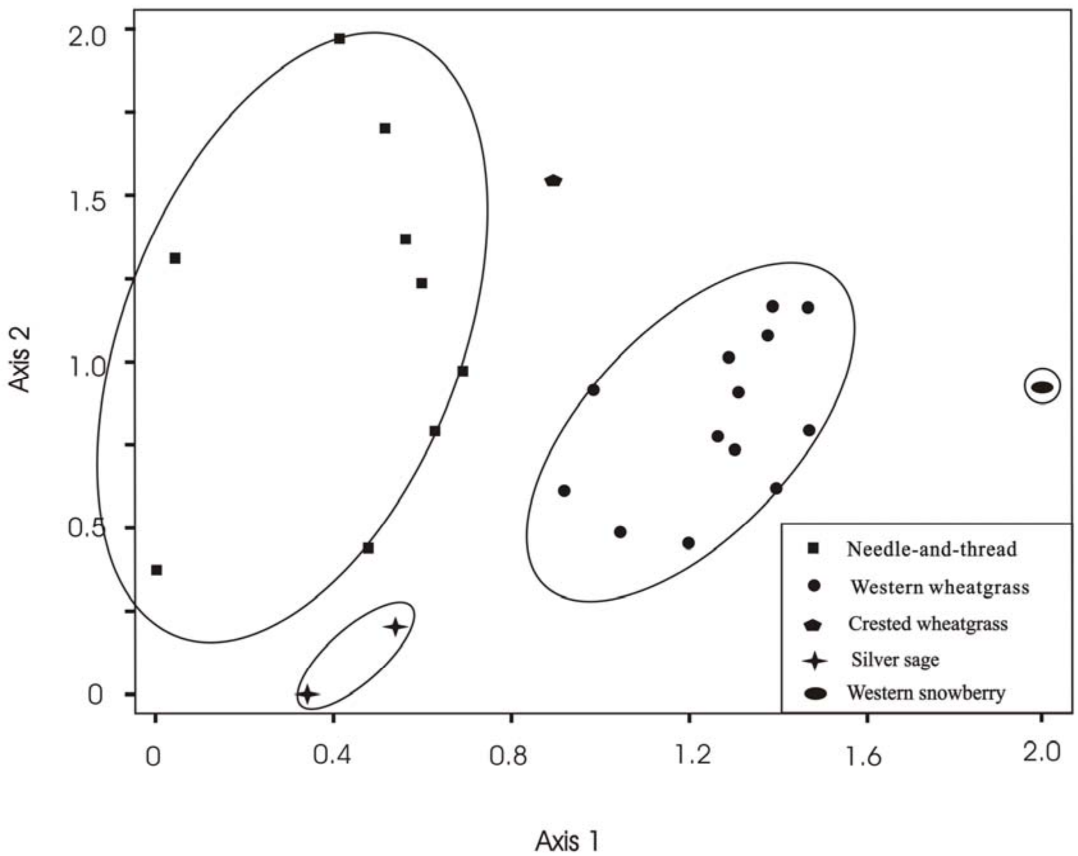
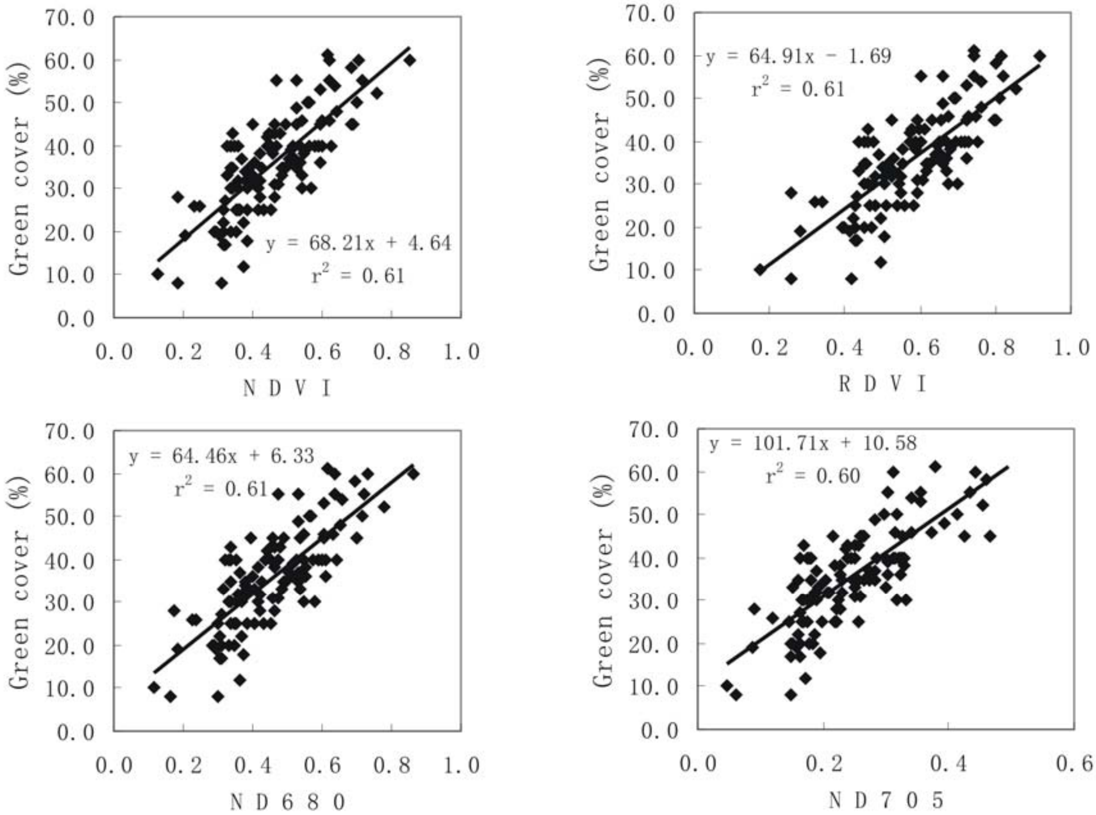


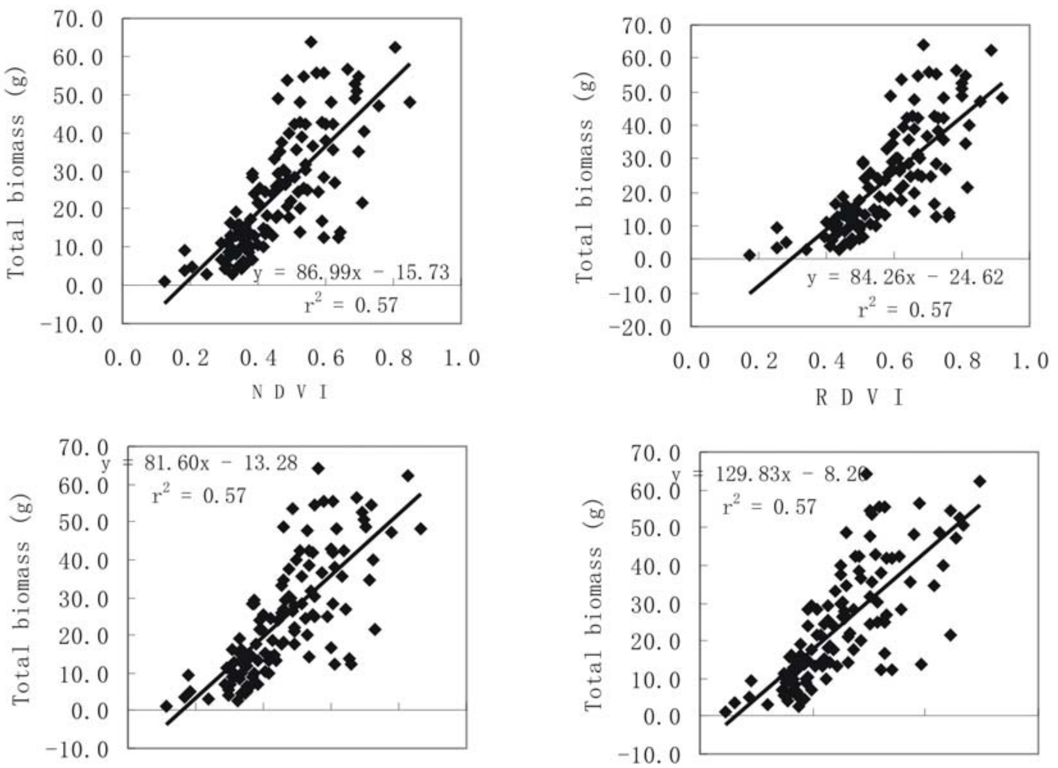
Figure 2.2 Detrended Correspondence Analysis (DCA) of transects data. The first axis explains about 56% of the variance in species composition and the second axis explains about 15% of variation. Separation along the first axis is related to gradients in soil moisture and

organic content. Separation along the second axis is slightly related to the slope angle. However, it is clear that the *Stipa* community can appear in areas with various slopes.

2.5.2 Relationships between biological parameters and spectral vegetation indices

Green vegetation cover (the sum of grass and forb cover), total biomass, and PAI showed strong and similar correlation with vegetation indices, with correlation coefficients of 0.78, 0.75, and 0.69 ($P<0.01$) respectively after being rounded to two decimal places. Their relationships can be simulated with linear regressions (Figure 2.3). Hyperspectral vegetation indices can explain approximately 47%, 57%, and 61% of the respective variations in PAI, total biomass, and green cover. NDWI only has a high correlation with green cover ($r = 0.76$, $P<0.01$) which might be explained by its sensitivity to canopy water content. The existence of non-photosynthetic materials in the canopy may decrease the correlation between NDWI and other biological variables. It seems reasonable for green cover and vegetation indices to have the highest correlation because vegetation indices are designed to extract information from green vegetation canopy and are therefore sensitive to its variation. Normally, biomass or production is positively related to vegetation cover (i.e., the higher the cover, the larger the biomass value). However, due to the accumulation of dead materials in the northern mixed prairie, the relationship between vegetation indices and total biomass is less conspicuous. An abnormal relationship is found between PAI and vegetation indices, as PAI has the lowest correlation with vegetation indices. The presence of standing dead


Green cover (%)
NDVI
y = 68.21x + 4.64
r2 = 0.61
RDVI
y = 64.91x - 1.69
r2 = 0.61
ND680
y = 64.46x + 6.33
r2 = 0.61
ND705
y = 101.71x + 10.58
r2 = 0.60


Total biomass (g)
NDVI
y = 86.99x - 15.73
r2 = 0.57
RDVI
y = 84.26x - 24.62
r2 = 0.57
ND680
y = 81.60x - 13.28
r2 = 0.57
ND705
y = 129.83x - 8.26
r2 = 0.57

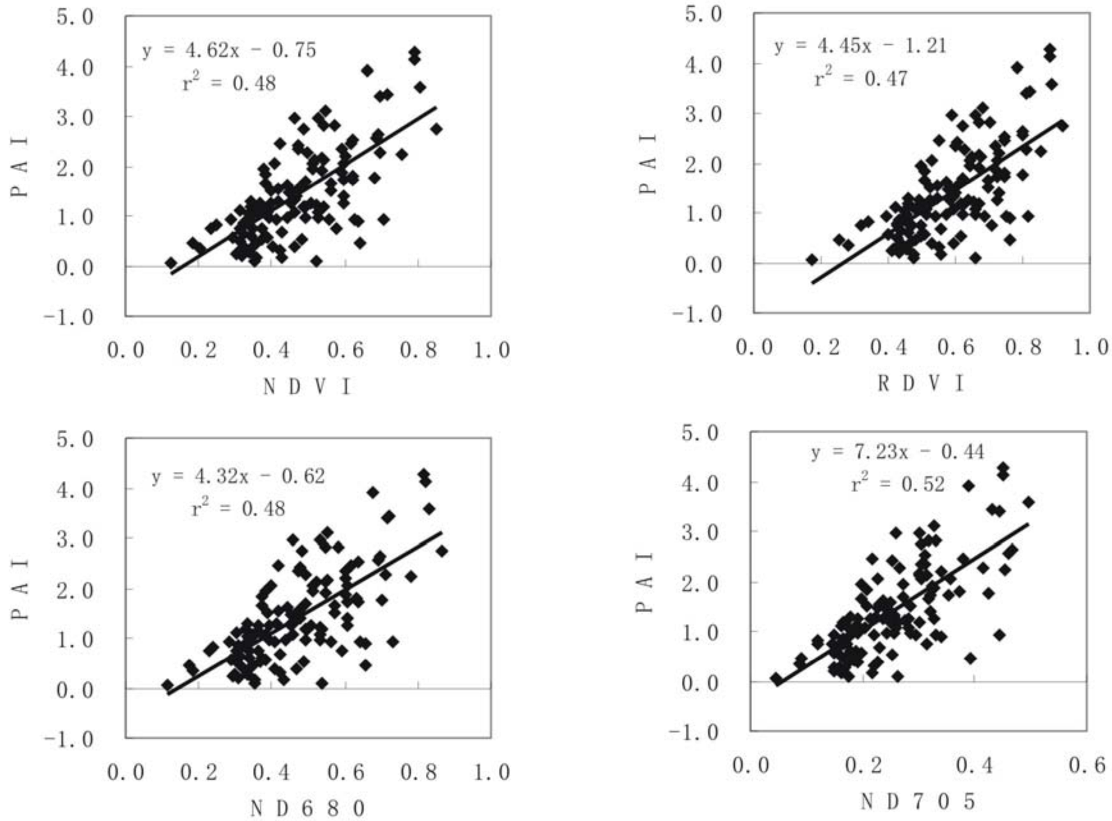


Figure 2.3 Relationships between grassland biological characteristics (green cover, total biomass, and PAI) and spectral vegetation indices (NDVI, RDVI, ND680, and ND705). Green cover is the sum of grass and forb.

materials exacerbates the relationship by influencing PAI measurement. The LiCor plant canopy analyzer measures the difference between light intensity above and below the canopy. As large amounts of standing dead materials in the canopy contribute to the measured PAI values, their correlation with vegetation indices is therefore abated. The influence of background effects on vegetation indices should also be considered. Vegetation in the northern mixed prairie is relatively sparse, such that there are often large gaps in most canopies. The relationship is further deteriorated by contributions from background effects, such as shadow, litter, biological crust (mainly moss and lichen), and bare ground, as they add noise.

Based on the linear regression, simulated broadband vegetation indices (NDVI and RDVI) are equally efficient at detecting green canopy as narrow band vegetation indices. The use of RDVI was not found to be necessary for this study, because the relationship between biological parameters and vegetation indices was almost linear. Stepwise regressions were applied to further test the relationships between vegetation indices and biological parameters. Results show that green vegetation cover and total biomass can explain about 72% of the variation in vegetation indices (Table 2.2), with ND705 and NDWI are more sensitive to the existence of standing dead materials in the canopy. NDWI is even influenced by the variation of forb cover, which is reasonable since forb species has higher turgidity than grass species. This indicates that both the cover and the density of the canopy may contribute to the reflectance being measured (i.e., the higher the density, the larger the vegetation index value). It is not surprising that PAI does not help to explain the variation of vegetation indices, due to the manner in which it is measured. Based on the above observation, it is reasonable to conclude that vegetation indices can be used to represent canopy condition (i.e., the greenness status). Therefore, it is logical to apply semivariogram analysis to vegetation indices, biological parameters, and environmental factors in order to reveal the spatial variation.

Table 2.2 Hyperspectral vegetation indices and biological parameters

Vegetation index	Model	R square	Adjusted R square	Standard Error
NDVI	0.15 + 0.006 X Green cover + 0.004 X Total biomass	0.72	0.72	0.069
RDVI	0.26 + 0.006 X Green cover + 0.004 x total biomass	0.72	0.72	0.071
ND705	0.03 + 0.004 X Green cover + 0.002 X litter cover + 0.003 X Grass biomass - 0.0003 X Standing dead cover	0.77	0.77	0.047
ND680	0.13 + 0.007 X Green cover + 0.004 X total biomass	0.72	0.72	0.073
NDWI	-0.40 + 0.008 X Green cover + 0.012 X grass biomass – 0.010 x Standing dead materials + 0.004 X Forb cover	0.72	0.69	0.10

2.5.3 Spatial scales for vegetation cover, biomass and PAI

There are large visible differences when examining the ranges of biological parameters. Ranges for green vegetation cover, grass cover, and forb cover are around 40m (Figure 2.4), which indicates that the size of the vegetation cover of the dominating communities is around 40 m. Forb cover has a larger average range (47.7 m) because of its small and stable cover percentage in the community. Similarly, standing dead materials have an exceptionally large range (120 m), which corresponds to the widespread of standing dead materials in the northern mixed prairie. PAI contains information on green cover, standing dead cover, and even other structure information of the canopy. It has a range value of 76 m, which is between standing dead materials and green cover, with the value closer to the ranges of green vegetation cover. While the influence of standing dead materials is less important than that of green vegetation cover (considering the fact that the percentage of standing dead material is generally smaller than that of green cover), it does make the variation of PAI smaller.

Ranges for biomass are slightly different than those for vegetation cover. Total biomass and grass biomass have ranges of 65 and 78 m respectively, which are larger than those for green vegetation cover. Therefore, the change of biomass is much more gradual when compared to that of green cover. The percentage of grass component in the vegetation canopy is relatively stable and consequently, grass biomass has a higher range than total biomass. While forb and grass cover have similar ranges, forb biomass has high variation (not shown) without an estimation of the range, which can be partly explained by the data collection process for biomass and the distribution of forb species. The quadrat size for biomass is 20 x 50 cm, which contributes to the large variations in forb cover (considering the sparsity of forb distribution). Dead material biomass (defined as the sum of litter and standing dead grass biomass) has the smallest value (34 m) (i.e., the largest variation) of all the biological parameters – even smaller than that of green vegetation cover. This large variation may be accounted for by different vegetation growth speeds and different litter accumulation speeds. In turn, the accumulation speed is primarily affected by changes in soil moisture. While the amount of dead materials is small in dry and sloped regions, the speed of accumulation is slow due to the small amount of vegetation growth. The accumulation speed is high where soil moisture is favorable for vegetation growth. Different ranges for biomass and covers can be explained by the various structures of vegetation canopy. Different grass, forb, and shrub species have different leaf and stem shapes, which make the variation of cover larger than that of the biomass.

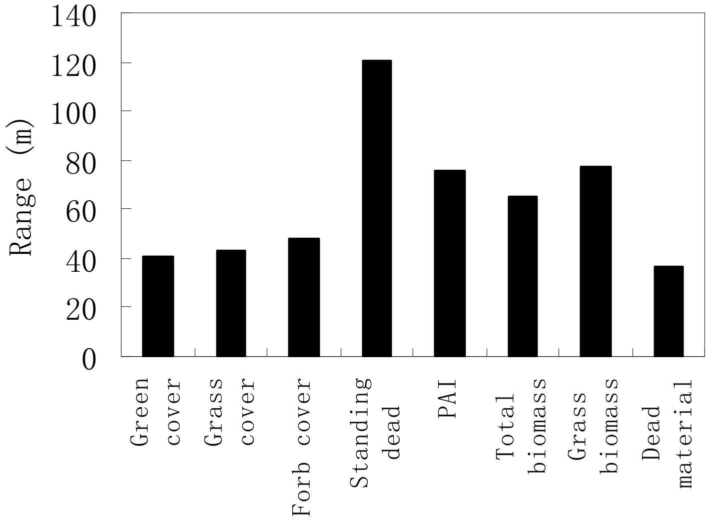


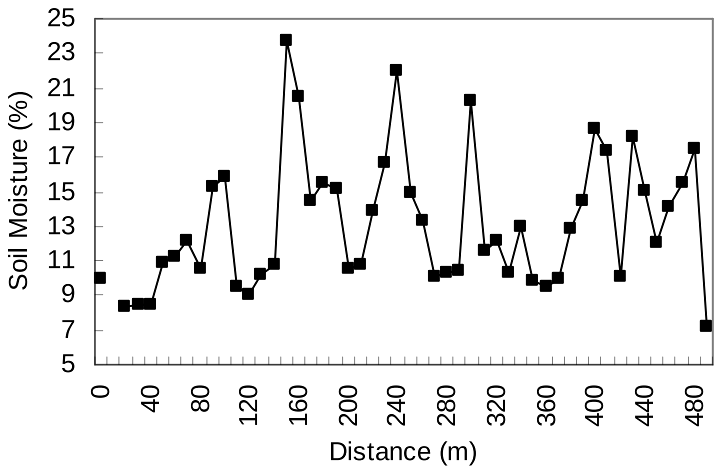
Figure 2.4 Ranges for estimated cover, PAI, and biomass, where standing dead and dead material represent standing dead cover and dead material biomass respectively.

2.5.4 Variations in environmental parameters and their roles in the spatial variation of vegetation growth

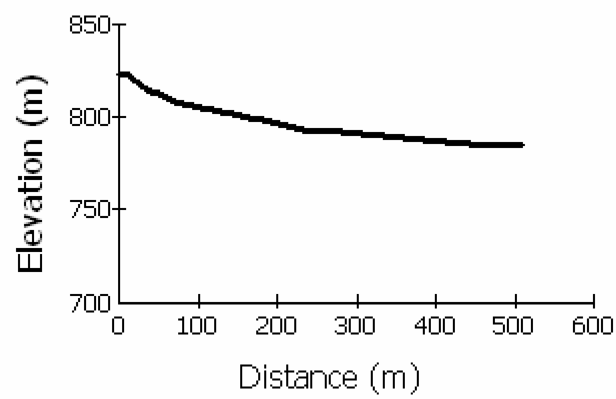
Soil moisture and organic content are the most influential environmental factors on vegetation growth in the semiarid environment of the northern mixed prairie (Si and Farrell 2004). PAI shows significant correlations with soil moisture and organic content significantly with r values of 0.41 and 0.46 respectively ($P<0.01$). Grass cover has slightly higher correlation coefficients with soil moisture and organic content (0.48 and 0.50 respectively, $P<0.01$). Shrub cover is comparatively more sensitive to soil moisture, with a correlation coefficient of 0.59 ($P<0.01$). Soil moisture is highly influenced by topographical parameters such as slope and upslope length (Zebarth and DeJong 1989, Moulin *et al.* 1994, Pennock *et al.* 1994). Therefore, vegetation growth is mainly controlled by topography through the key role of soil moisture, a fact that was also demonstrated in my field observations. The influences of topography on the vegetation community are so important that Rey-Benayas and Pope (1995) even used a topographic index to infer biological heterogeneity (vegetation richness): the more uniform the landscape, the lower the variation. In other words, biological heterogeneity is most likely to be positively correlated with landscape heterogeneity (Burnett *et al.* 1998), where topography and soil moisture are important components. The variation of soil moisture is mostly controlled by topography; therefore, it is feasible to use it as a representation of topography in this study (Figure 2.5). It is obvious that there are periodic spatial changes in soil moisture along the transect and that the distance of the average cycle is approximately 60 m.

Bulk density is one indicator of the soil's physical structure, which also influences vegetation growth (Blake and Hartge 1986). Bulk density, organic content, and soil moisture have similar ranges (55.8, 53.6, and 53.4 m respectively) with bulk density as the highest and soil moisture as the lowest. While soil moisture is more variable due to the direct influence of slope and upslope length, bulk density is slightly more homogeneous, as it is influenced by the soil parent materials, trampling, and other factors. Compared with results from the previous section, ranges in vegetation cover are smaller than those for environmental factors, which indicates that though these factors influence to vegetation cover, there are other determining factors such as wind, trampling, wildlife grazing, and species competition, all of which make the variations in vegetation growth larger than those caused by environmental factors.

For biomass, the situation is slightly more complex; dead material biomass has a smaller scale of 36.6 m while total biomass and grass biomass have larger scales (66.4 and 77.7 m respectively). Biomass accumulation is not only influenced by annual vegetation growth, but also by the accumulation of dead materials. High soil moisture is favorable for vegetation growth, which therefore speeds up the accumulation of dead materials. These accumulated dead materials, in turn, influence vegetation growth by retaining soil moisture, decreasing soil temperature, and improving vegetation growth. However, over-accumulated dead materials may block vegetation growth, which is especially true in some areas of the park due to the removal of cattle. It is possible that soil moisture, organic content, bulk density, and other factors work together to create smaller variations (larger scales) for total biomass and grass biomass. It also proves that the variance of landscape properties is a function of scale (Bian 1997). Therefore, the variation of environmental factors (which are controlled by landscape properties) should be considered when measuring biological parameters.



(a)



(b)

Figure 2.5 Variation of soil moisture along the 500 m transect from upland to valley grassland (a) and its elevation profile (b). The profile is obtained from a 1:50,000 contour map. Therefore, its resolution is too coarse to show the variation of elevation at small scale.

2.5.5 Dominant community sizes and variation in average canopy height

There is no range estimated for needle-and-thread. It normally appears in dry spots (i.e. upland and sloped grasslands) with varying slope and soil moisture (as shown in Figure 2.2). It rarely appears in the valley grasslands (where clay soil dominates) even though most places in the valley grasslands are dry. In the field records, it even appeared in some quadrats where soil moisture is relatively high (>15%). It is possible that I failed to differentiate needle-and-thread with western porcupine grass (*Stipa curtiseta*), which favors moister sites. Therefore, this anomaly or possible error hinders the estimation of its range. June grass (*Koeleria gracilis*) is also widely spread in the grasslands and it showed only a sill value (data not shown), which can be explained by its life forms. It has two life forms, basal in dry spots and with stems in moist habitats (Looman 1982). This situation is similar to that of needle-and-thread. The range for western wheatgrass is 30 m, which can be explained by the influences of soil moisture. Its range of spatial variation is only half of the scales for environmental factors, because it flourishes only in places where soil moisture is high. Blue grama grass (*Bouteloua gracilis (HBK*) *Lang. ex Steud*.) shows a periodic empirical variogram (data not shown) because of the important influences of cyclic variations in soil moisture. It normally appears in dry and clay loam soil. Range for average canopy height, one indicator of vegetation growth, is 45.9 m, which is close to that of the environmental factors, indicating that vegetation height is mostly correlated with them, though other factors (e.g., grass species, competition, and grazing) also contribute to the variation (Hurd, 1959).

2.5.6 Spatial scale of spectral vegetation indices

Spatial scales for vegetation indices are around 55 m (NDVI and ND705) and 66 m (RDVI and ND680) (Figure 2.6). All vegetation indices, except NDWI, have larger scales than vegetation covers and smaller scales than PAI, standing dead materials, and biomass (except dead material biomass). Remotely collected hyperspectral data tend to homogenize the variation, especially the variation measured in green vegetation cover, because they contain information for other parameters (e.g. standing dead materials and canopy structure) which have smaller scales. Apart from green vegetation and dead materials in the canopy, they also contain background information such as shadow, biological crust, and bare ground. Thus, two quadrats with different green vegetation cover and standing dead materials may have the same values on vegetation indices, as has been demonstrated by the field observations. Therefore, information conveyed in vegetation indices is a mix of all the attributes or features. As a result, the spatial scales calculated from vegetation indices are a compromise of scales from all the biological parameters. Interestingly, NDVI and ND705 have similar ranges, as do RDVI and ND680, which indicates that these two groups of vegetation indices represent information at different scales. NDVI and ND705's ranges are the same as those of environmental factors but RDVI and ND680 are closer to the ranges for total biomass. This may indicate that the ranges of these indices are indirectly controlled by environmental factors, and that different vegetation indices can be used to extract information for different biological properties (e.g., RDVI and ND680 are better for total biomass). However, neither RDVI nor ND680 are better able to extract information of total biomass (as shown in regression analysis). NDWI is an anomaly amongst these indices, with a scale of 31 m it is even smaller than that for dead materials. Differing from the other four vegetation indices, NDWI is more sensitive to the change in canopy moisture, which is highly related to the change in soil moisture, vegetation species, and canopy density. Therefore, it is reasonable that it has a higher variation than the other vegetation indices, soil moisture, and even dead biomass, which represents a scale smaller than those of other vegetation indices.

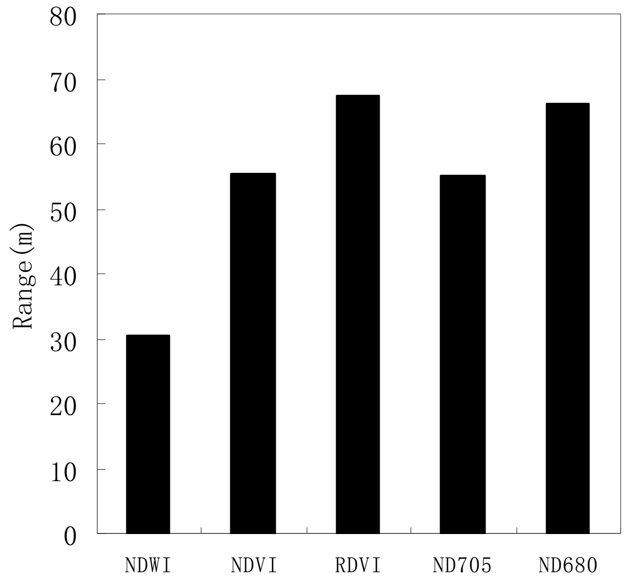


Figure 2.6 Ranges for spectral vegetation indices from semivariogram analysis

2.5.7 Scales for biological parameters in the northern mixed prairie

It is clear from the previous discussion that the measured range of variance is different for different parameters; with standing dead material cover having the largest range (120 m) and dead material biomass having the smallest (34 m). Ranges from semivariogram are related to the size of dominant objects being studied (Woodcock *et al.* 1988, St-Onge and Cavayas 1995, Treitz and Howarth 2000), which, in this scenario, is related to community size. The spatial scale of biological parameters in the northern mixed prairie should be the same as the range, spanning from 34 to 120 m. Therefore, the results from a single parameter may lead to an improper resolution, given the large difference between 34 m and 120 m. As a result, it is advisable to determine different spatial scales for different biological parameters according to the objectives of the research, in order to capture the variation of the biological parameters. After comparing the spatial scales of vegetation indices and biological parameters, it is clear that vegetation indices can be representative of biological parameters in studies of spatial variation. According to sampling theory, the most appropriate resolution for detecting biological heterogeneity should be 1/3 to 1/5 of the range/scale (Houlding 2000). Therefore, the most appropriate resolution should be around 10 – 20 m for northern mixed prairie.

Spatial scales for biological parameters were highly related to soil moisture, organic content, and bulk density, with topography being one of the most important factors for the variation. In another study conducted by He *et al.* (2006) for the same study area (which focuses only on upland only), they concluded that topography determines the vegetation spatial scale at landscape level and soil moisture controls the vegetation spatial variation at smaller scale. They also concluded that a 20 m resolution is optimal for studying grassland heterogeneity in accordance with topography variation, which coincides with the results.

2.6 Conclusions

As the first comprehensive study of the biological heterogeneity of the northern mixed prairie, the following conclusions can be drawn from this study. First, there are large differences between plant communities in upland grassland and valley grasslands. The variation between these communities can be partly explained by changes in environmental factors (soil moisture and organic content) due to topographical influences. Second, both simulated vegetation indices and narrow band vegetation indices can be used to represent biological parameters. NDVI, RDVI, ND705, ND680, and, NDWI are useful at detecting PAI, total biomass, and green vegetation cover. They can explain about 40 – 60% of the biological variation. Finally, when considering the spatial scales, there are different spatial variations for different biological parameters. The spatial scale of variation from upland grassland to valley grassland for biological parameters from 34 m to 120 m, where standing dead materials has the largest range. The scales for vegetation indices are similar to the scales for total biomass and environmental factors. Therefore, it is reliable to use the scale of the spectral vegetation indices to decide the spatial scale of the green vegetation growth. The recommended spatial resolution for the northern mixed prairie can be set at 10 – 20 m to discern the conspicuous biological variations from upland to valley grasslands.

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CHAPTER 3 - MONITORING NORTHERN MIXED PRAIRIE HEALTH USING BROADBAND SATELLITE IMAGERY

3.1 Abstract

The mixed prairie in Canada is characterized by its low to medium green vegetation cover, high amount of non-photosynthetic materials, and ground level biological crust. It has been proven a challenge for the application of remotely sensed data in extracting biological parameters for the purpose of monitoring grassland health. Therefore, this study was conducted to evaluate the efficiency of broadband based reflectance and vegetation indices in extracting ground canopy information. The study area was Grasslands National Park (GNP) Canada and the surrounding pastures, which represent the northern mixed prairie. Fieldwork was conducted from late June to early July, 2005. Biological variables – including canopy height, cover, biomass, and species composition – were collected for 31 sites. Two satellite images, one SPOT 4 image on June 22, 2005 and one Landsat 5 TM image on July 14, 2005, were collected for the corresponding time period. Thirteen vegetation indices were calculated based on surface reflectance. Pearson correlation and regression analysis were applied to study the relationships between vegetation indices and biological parameters. Results show that the spectral curve of the grass canopy is similar to that of the bare soil with lower reflectance at each band. Consequently, commonly used vegetation indices are not necessarily better than reflectance when it comes to single wavelength regions extracting biological information. Reflectance, NDVI, ATSAVI, and two new created cover indices are

good at extracting biological information.

Key words: Remote sensing, broadband, mixed prairie, vegetation index, prairie health, SPOT,

3.2 Introduction

As a pool of carbon dioxide and a gene pool of wildlife and vegetation, the mixed prairie of North America is an important component of the global ecosystem (Coupland 1992). Most mixed prairies have been transformed to cultivated or ranch land for long time periods (Lauenroth *et al*. 1994). As a result, the original mixed prairie plant community disturbed by bison and fire has different secondary succession, which largely changed the ecosystem condition. Therefore, it is important to evaluate and monitor grassland health to make sure that we have a sustainable grassland ecosystem. Grassland health is ‘the degree to which the integrity of the soil and the ecological processes of grassland ecosystem are sustained’ (National Research Council, 1994). Generally, contents of grassland health include: soil stability, watershed function, and recovery mechanism (National Research Council, 1994) with soil stability being one of the most important factors of grassland health (National Research Council 1994, Pyke *et al*. 2002). To monitor grassland health using satellite remote sensing, indicators are necessary to fulfill and simplify the process. Measurements can be made from two aspects: soil degradation and plant growth (National Research Council 1994). Specifically information on percentage of bare ground, biomass, and vegetation cover should be extracted first as an initial step towards grasslands health evaluation.

Based on conclusions formed last chapter, it is reliable to use broadband vegetation indices from SPOT and Landsat for monitoring vegetation ecosystem dynamics due to their simplicity and efficiency. Many vegetation indices have been developed and applied in vegetation studies since the proposal of the first vegetation index, Ratio Vegetation Index (RVI) (Jordan 1969, Broge and Leblanc 2000). Even though remote sensing has been used in different grassland ecosystems, --such as tallgrass prairie (e.g., Asrar *et al*. 1986, Asrar *et al*. 1989, Guo *et al*. 2003), short grass prairie (e.g. Lauver 1997), and other grassland types in semiarid and arid environment-- (e.g., Wilson 1989, Lewis 1994, Dilley *et al*. 2004) for more than two decades, only a few studies have been conducted in the mixed prairie using medium resolution satellite imagery (Guo *et al*. 2005, Zhang *et al*. 2005, Zhang *et al*. 2006). There has not been a comprehensive study to monitor the northern mixed prairie health using remote sensing techniques.. Therefore, this study aims to investigate the spectral characteristics of the northern mixed prairie during the full growing season and to seek the possibility of extracting biological parameters for the evaluation of grassland health.

3.3 Study Area

The study area includes the Grasslands National Park (GNP) (49° N, 107° W) and surrounding pastures located in southern Saskatchewan along the Canada - United States border. This area falls within the mixed prairie ecosystem (Coupland 1992). The park is approximately 906 km^2 in area, consisting of two discontinuous blocks, west and east. Land was first acquired for the park in 1984; hence, some areas of the park have been under protection from livestock grazing for over 20 years. The park area consists of upland, sloped, and valley grasslands. The dominant plant community in the uplands is needle-and-thread – blue grama grass (*Stipa-Bouteloua*), which covers nearly two thirds of the park's ground area. The dominant grass species in this community include needle-and-thread (*Stipa comata Trin. & Rupr.*), blue grama grass (*Bouteloua gracilis (HBK*) *Lang. ex Steud.*), and western wheatgrass (*Agropyron smithii Rydb.*). Comparatively, valley grasslands are dominated by western wheatgrass and northern wheatgrass (*Agropyron dasystachym*) along with higher densities of shrubs and occasional trees. The sloped grassland is a transitional area with species from both upland and valley grassland. The GNP area has a mean annual temperature of 3.8 ºC and a total annual precipitation of 325 mm (Environment Canada 2003). Approximately half of the precipitation is received as rain during the growing season. Common soils in the Park areas are chernozemic soils and solonetzic soils (Fargey *et al*. 2000). Chernozemic soils are the most common in grassland communities, with a dark color and high amount of organic content. Solonetzic soils, with their high salinity and lighter color, are formed due to the drought and high evaporation. Under the sparse vegetation canopy in the Park area, a large part of the surface is covered by microphytic communities of small non-vascular plants. These microphytic communities include mainly mosses and lichens, which form biological crusts over soils and rocks. Biological soil crust is an important component of the semiarid and arid grasslands. Its roles include the breakdown of humus, the release of nutrients, and the protection of soil from water erosion (Kauffman and Pyke 2001).

3.4 Field Work and Data Preprocessing

Field work was conducted in June and July of 2005, the maximum growing season of the northern mixed prairie. Thirty-one sites were distributed in the upland (10 sites), sloped (7 sites), and valley grassland (14 sites). These sites were decided by stratified random sample design and their accessibility. Two 100×100 m plots were set up in each site. Each plot was composed of two 100 m transects placed perpendicularly to each other which intersected in the centre to form a cross. Twenty-one quadrats (50×50 cm) were placed in each plot at 10 m intervals. Percent cover of grass, forb, shrub, standing dead, litter, moss, lichen, and bare ground − as well as species composition − were collected at each quadrat. Litter, moss, lichen, and bareground counted as understory. Due to the restriction of the Park, biomass was collected at 20 m intervals with a 20×50 cm quadrat using the harvesting method. Clipped fresh biomass was sorted into four groups; grass, forb, shrub, and dead materials. They were then dried in an oven for 48 hours at 60 ºC. Plant Area Index (PAI, projected area of all vegetation parts normalized by the subtending ground area) was measured using a LiCor-PAI-2000 Plant Canopy Analyzer. At each quadrat, PAI was the result of one above canopy reading compared with 9 below canopy readings. The sensor was shaded when observations were being taken to reduce the glare effect from direct sunshine. All biological parameters were averaged by sites.

3.5 Methods

3.5.1 Satellite imagery and preprocessing

A SPOT 4 HRVIR image with 20 m resolution and a Landsat 5 Thematic Mapper (TM) image with 30 m resolution were collected for the field campaign on June 22 and July 14, 2005 respectively. Geometric, atmospheric, and radiometric corrections were applied on both images. The geometric correction was done with an accuracy of better than 0.3 pixel (RMSE < 6m) for SPOT and 0.5 pixel (RMSE < 15m) for Landsat image. Both images were registered to the Universal Transverse Mercator (UTM) projection and the nearest neighbour method was used in resampling. Atmospheric corrections were conducted based on Chavez's improved dark object image subtraction approach (Chavez 1988) due to the lack of historical atmospheric data. Similarly, an algorithm ATCOR2 from PCI Geomatics was applied to the SPOT 4 imagery to remove the influences from atmosphere. The process of radiometric correction followed the procedure of Markham and Barker (1986). Different parameters were applied to the SPOT image.

3.5.2 Vegetation indices

To study the canopy characteristics spectral curves for typical mixed prairie, bare soil and crested wheatgrass (green healthy vegetation) were first extracted by visually identifying these ground features. Vegetation indices evaluated by Chen (1996) and Peddle *et al*. (2001), TSAVI, and ATSAVI were then calculated. These vegetation indices can be categorized as four groups; ratio, orthogonal, hybrid, and nonlinear (Chen, 1996; Broge and Leblanc, 2000). The most commonly used vegetation index, Normalized Difference Vegetation Index (NDVI), is one of the ratio vegetation indices. NDVI is also the most commonly used vegetation index in grassland study which has been widely used to evaluate cover (Dymond *et al*. 1992), above-ground biomass (Tucker 1985), chlorophyll content (Tucker 1985), leaf area (Asrar *et al*. 1986, Curran *et al*. 1992), phenology (Markon *et al*. 1995), absorbed photo-synthetically active radiation (Prince 1991), and Net Primary Productivity (NPP) (Ruuning 1989). However, NDVI is influenced by many environmental factors such as topography, bare soil (soil fraction, soil type, and soil moisture), atmospheric condition (Pinty and Verstraiet 1992), vegetation association, rainfall (Schmidt and Karnieli 2002), and non-photosynthetic materials (Gamon *et al*. 1993). Therefore, adapted vegetation indices − for example hybrid, orthogonal, and nonlinear indices − have been proposed to deal with the influences of background information (Table 3.1). Huete (1988) developed a Soil Adjusted Vegetation Index (SAVI) using a soil adjustment factor, which is decided by percentage of green cover, to adjust for the influence of soil in the spectral features. Unfortunately, the requirement of knowing percentage vegetation cover beforehand could not always be met in many cases due to the lack of ground truth data. As a result, Qi *et al*. (1994) improved the performance of SAVI by proposing Modified Soil Adjusted Vegetation Index (MSAVI) and the second Modified Soil Adjusted Vegetation Index (MSAVI2) with an additional dynamic soil adjusting factor. Baret (1989) introduced the Transformed SAVI (TSAVI) and Adjusted TSAVI (ATSAVI) by taking into account the soil line slope and intercept. Pinty and Verstraete (1992) developed a Global Environmental Monitoring Index (GEMI) to correct for the atmospheric contribution in Advanced Very High Resolution Radiometer (AVHRR) data specifically. Generally, hybrid vegetation indices are good for vegetation canopy of low cover (Ray 1994). Orthogonal indices are different from ratio indices for the position of the greenness isolines (Broge and Leblanc 2000). The Weighted Difference Vegetation Index

(WDVI) is a typical orthogonal index. They are not sensitive to soil background because they are parallel to the principle axis of soil spectral variation. Because the relationship between vegetation indices and biological parameters is not necessarily linear, nonlinear indices, the Nonlinear Index (NLI) and the Renormalized Difference Vegetation Index (RDVI) were developed to linearize their relationships with surface parameters (Chen 1996).

Considering the fact of litter accumulation (which highly influences the canopy moisture condition), it is possible that vegetation canopy information can be indirectly extracted by detecting canopy moisture condition. Therefore, the Normalized Difference Moisture Index (NDMI) and two new indices, Normalized Difference Cover Index (NDCI) and Ratio Cover Index (RCI), were also calculated to seek the possibility of using them to detect biological parameters. NDCI and RCI are two new indices which combine reflectance from red and SWIR bands. These two new cover indices are created based on the fact that there are high correlations between Red, SWIR, and biological parameters in the mixed prairie. This is mostly induced by the accumulation of dead materials and litter, which significantly changes moisture condition of the vegetation canopy and soil moisture. Therefore, it is possible to combine these two bands together. Altogether thirteen vegetation indices were calculated (Table 3.1).

Vegetation indices were averaged using a 5×5 (100×100 m) window for SPOT image and a 3×3 window (90×90 m) for Landsat 5 TM image centered at each plot on every site, to correlate with field measured parameters. The Shapiro-Wilk test was applied to check the normality of the dataset. Data were transformed so as to be close to a normal distribution. Pearson's correlation analysis was conducted for all biological parameters and vegetation indices. Stepwise regression analyses were run to identify the relationships between biological variables and vegetation indices. Linear or nonlinear regression analyses were run to identify indices best suited to estimate the biological parameters. Prediction models were developed for biological parameters and the results were validated with the Jack-knife cross validation method, which withdraws one sample each iteration and runs the model for n-1 iterations.

Furthermore, spectral linear unmixing method (Gong *et al.* 1991, Okin *et al.* 2001) was applied to seek the possibility of obtaining subpixel information. Only reflectances from grass, bare ground, and litter were used as endmembers because there are only 4 bands can be used.

3.6 Results

3.6.1 Species composition, dominant species, and vegetation canopy characteristics

The name of the mixed prairie indicates that no single species dominates a plant community as in other grassland ecosystems. In the study area, needle-and-thread (*Stipa comata* Trin. & Rupr.), blue grama grass (*Bouteloua gracilis*), and western wheatgrass (*Agropyron smithii* Rydb.) are dominant species (Table 3.2), with needle-and-thread having the highest percentage cover in all sites in the upland grassland. Communities in upland and sloped grassland are mostly dominated by needle-and-thread while communities in valley grassland (or in depressions in upland grassland) are dominated by western wheatgrass and

Table 3.1 Vegetation indices used in this study. NIR, RED, and SWIR indicate reflectance from near infrared, red, and short (for SPOT) or middle (for Landsat) infrared wavelength regions respectively.

Category	Vegetation index	Equation	References
Ratio Vegetation index	Simple Ratio (SR) or Ratio Vegetation Index (RVI)	$\frac{NIR}{RED}$	Jordan 1969
	NDVI (Normalized Difference Vegetation Index)	$\frac{NIR-RED}{NIR+RED}$	Rouse *et al*. 1973
Hybrid Vegetation Index	SAVI (Soil-adjusted vegetation index)	$\frac{NIR-RED}{(NIR+RED+0.5)}\times(1+0.5)$	Huete 1988
	TSAVI (Transformed Soil-adjusted Vegetation Index)	$\frac{1.219\times(NIR-1.219\times RED-0.029)}{1.219\times NIR+RED-1.219\times 0.029}$	Baret 1989
	ATSAVI (Adjusted Transformed Soil-adjusted Vegetation Index)	$\frac{1.219\times(\mathrm{NIR}-1.219\times RED-0.029)}{1.219\times NIR+RED-1.219\times 0.029+0.08\times(1+1.219^2)}$	Baret and.Guyot 1992
	MSAVI2 (Second Modified Soil Adjusted Vegetation Index)	$\frac{2\times\mathrm{NIR}+1-\sqrt{(2\times\mathrm{NIR}+1)^2-8\times(\mathrm{NIR}-\mathrm{RED})}}{2}$	Qi *et al*. 1994
	Global Environmental Monitoring Index (GEMI)	$eta\times(1-0.25\times eta)-\frac{RED-0.125}{1-RED}$ where eta = $\frac{2\times(\mathrm{NIR}^2-\mathrm{RED}^2)+1.5\times NIR+0.5\times\mathrm{RED}}{NIR+RED+0.5}$	Pinty and Verstraiet 1992
Orthogonal Vegetation Index	WDVI (Weighted Difference Vegetation Index)	$\mathrm{NIR}-1.219\times\mathrm{RED}$	Clevers 1989
Nonlinear Vegetation Index	RDVI (Renormalized Difference Vegetation Index)	$\frac{NIR-RED}{\sqrt{NIR+RED}}$	Roujean and Breon 1995
	NLI (Non-Linear Index)	$\frac{NIR^2-RED}{NIR^2+RED}$	Goel and Qin 1994
	NDMI (Normalized Difference Moisture Index)	$\frac{NIR-SWIR}{NIR+SWIR}$	Hardisky *et al*. 1983
	Normalized Difference Cover Index (NDCI)	(SWIR – Red) / (SWIR + Red)	
	Ratio Cover Index (RCI)	SWIR / Red	

northern wheatgrass. Differences between these two groups mainly exist in soil moisture, topography, and soil characteristics. Needle-and-thread dominates in dry upland soils and is rare in clay soils. Western wheatgrass and northern wheatgrass are rhizomatous and flourish on clay and clay loam soils, which is the case for valley grasslands. As the dominant C4 grass species in the northern mixed prairie, blue grama grass appears in dry and clay loam soil. Silver sagebrush (*Artemisia cana*) is one of the most common shrub species in the valley grasslands. Forb species, such as narrow-leaved collomia (*Collomia linearis Nutt.*) and pasture sage (*Artemisia frigida*) were also commonly found in each site with slight changes of cover from site to site.

Table 3.2 Dominant species in the west block of the Grasslands National Park and surrounding area and their average cover.

Common name	Scientific name	Average cover (%)
Needle-and-thread	*Stipa comata* Trin. & Rupr.	17.5
Western wheatgrass	*Agropyron smithii* Rydb.	8.3
Blue grama grass	*Bouteloua gracilis*	6.2
Threadleaf sedge	*Carex filifolia* Nutt.	5.3
June grass	*Koeleria macrantha* (Ledeb.) J.A. Schultes f.	3.4
Pasture sage	*Artemisia frigida*	3.1
Moss phlox	*Phlox hoodii*	2.2
American vetch	*Vicea Americana*	1.5
Silver sagebrush	*Artemisia cana*	1.2

The mixed prairie is noted for its low vegetation cover, large amount of dead material, and biological crust (Table 3.3). At the canopy level the grass and forb covers are 16.8% and 5.4% respectively, along with 11.1% for standing dead materials. The sparse canopy resulted in low biomass with an average above ground total biomass of 261.0 g/m^2. A large amount of dead materials, including standing dead materials and litter, have been accumulated in the northern mixed prairie, especially in the park area. This is mainly due to the removal of grazing cattle. Dead materials account for about 50.0% of total biomass and cover 38.1% of the understory. Moss and lichen are important components of understory biological crust in the northern mixed prairie with 32.7% and 8.6% cover respectively. Furthermore, there are large variations between grassland in different topography, especially valley grassland and upland grassland (Table 3.3). For the canopy level, there are more shrub communities (5.6% vs 0.2%, $P<0.01$) and less standing dead cover (5.6% vs 12.7%, $P<0.01$) in the valley grassland. For the ground level, there is a high percentage of bare ground in the valley grassland (31.4% vs 0.9%, $P<0.01$). There is less biological crust (moss plus lichen) in the valley grassland (22.6% vs 57.8%, $P<0.01$). Sloped grassland is similar to the upland grassland with fairly close canopy cover. Though there are more standing dead materials (14.0% vs 12.7%) and litter (39.7% vs 35.8%) in the sloped grassland, the differences are not significant. The main reason may be the difficulty of grazing in the sloped areas. However, the rock/bare soil percentage is the largest in the sloped grassland ($P<0.01$).

Table 3.3 Vegetation canopy characteristics for different topography types. Canopy cover was estimated at both canopy and ground level. Canopy level cover was recorded both as a whole and by species. Lichen, moss, litter, bare soil, and rock were recorded at ground level.

	Canopy cover (%)				Ground level (%)				
	Grass	Forb	Shrub	Standing Dead	Litter	Moss	Lichen	Rock	Bare ground
Sloped	17.2	6.8	1.1	14.0	39.7	35.5	12.6	5.9	5.3
Upland	19.8	6.0	0.2	12.7	35.8	52.0	5.8	1.2	0.9
Valley	14.1	3.5	5.6	7.1	38.2	16.0	6.6	2.6	31.4
Average	16.8	5.4	2.5	11.1	38.1	32.7	8.6	3.5	13.8

3.6.2 Spectral characteristics of the northern mixed prairie

Reflectance curves for bare soil, the mixed prairie, and crested wheatgrass extracted from SPOT and Landsat images are shown in Figure 3.1. Crested wheatgrass (*Agropyron cristatium*) indicates the cropland south of Val Marie mainly for bales, where crested wheatgrass is the main vegetation species. Spectral curves for bare soil and crested wheatgrass are for the purpose of comparison.

Differences between the grassland, bare soil, and crested wheatgrass are very clear. The crested wheatgrass has a typical spectral curve for green vegetation canopy, a red trough, an NIR peak, and low in SWIR. The reflectance of the grassland however, even during the maximum growing season, is significantly different from the crested wheatgrass at each band (typical green vegetation, $P<0.01$). Compared with the green crested wheatgrass, the mixed prairie has higher reflectance at red, green, and middle infrared wavelength regions. In contrast, it has lower reflectance at near infrared wavelength region. This reflectance curve of the mixed prairie is similar to that of the bare soil, with its value lower at each wavelength region. The SPOT image was taken in the maximum growing season; therefore reflectance at the green band is higher than reflectance at the red band for the mixed prairie. The Landsat 5 TM image was taken at a later date, corresponding to the late growing season for most native grass species while they were brown. With the progress of senescence, chlorophyll in the leaves may disappear and carotenes and other pigments can become dominant (Jenson 2000). Consequently the canopy will show a brown color. Therefore, reflectance for red (especially for the mixed prairie) is higher than that of green where the senescence process plays a large

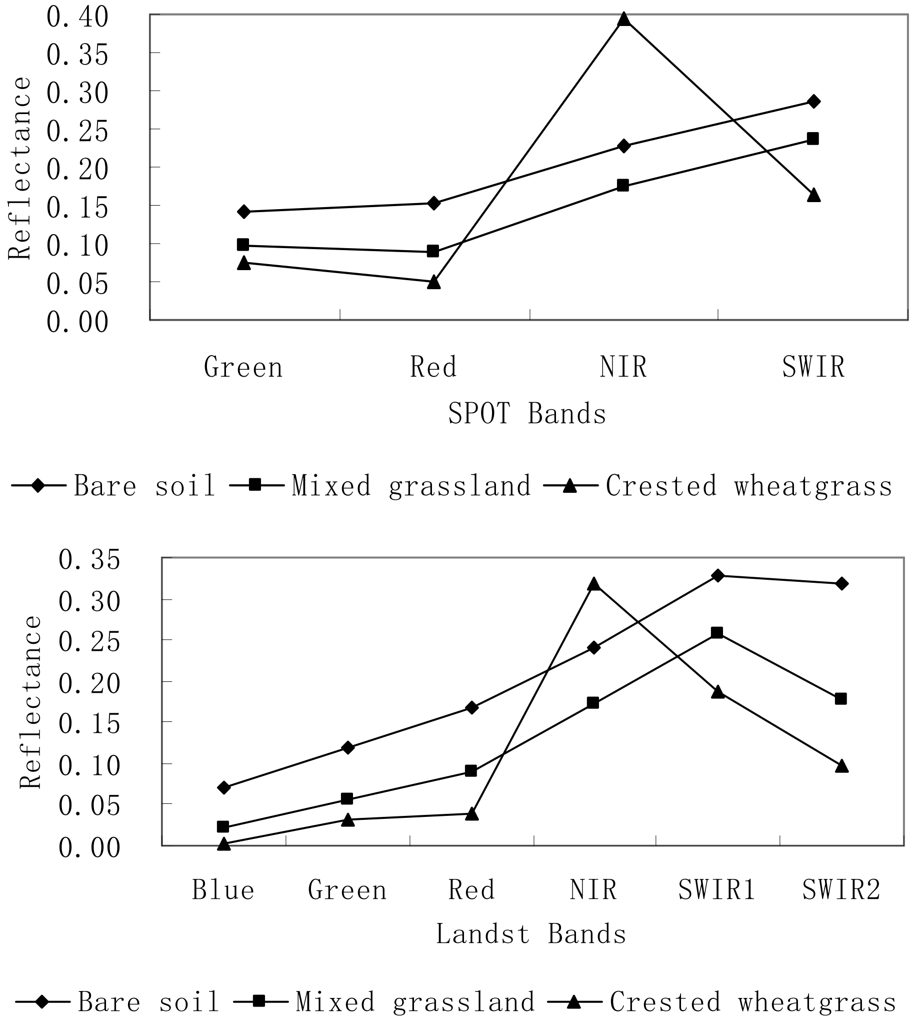


Figure 3.1. Reflectance of bare soil, crested wheatgrass, and the mixed prairie. Reflectance values were extracted from (a) SPOT 4 HRVIR on June 22, 2005; (b) Landsat 5 TM on July 14, 2005. Crested wheatgrass indicates croplands close to Val Marie mainly used for bales and the main grass species is crested wheatgrass (*Agropyron cristatium*). There is very sparse vegetation cover above the bare soil (< 5%) mainly in the valley and sloped grassland. Therefore, the reflectance for bare soil at different bands is low compared to pure bare soil.

role, as in the Landsat image. Similarly, the reflectance at the NIR band for the mixed prairie is much lower than that of the crested wheatgrass due to the sparse canopy. The transmitted energy through the leaf layer absorbed by the ground cover beneath the vegetation canopy makes the reflectance low at the near infrared band (Jensen 2000). Similarly, the northern mixed prairie has specific spectral properties at the SWIR band. The SWIR band is related to the canopy moisture. As the amount of plant water in the intercellular air space decreases, the incident middle-infrared energy is more strongly scattered at the interface of the intercellular walls resulting in greater SWIR reflectance from the leaf (Jenson 2000). The mixed prairie has fairly sparse canopy, therefore its canopy moisture is lower than that of the crested wheatgrass. Consequently, it is reasonable that reflectance of the SWIR band of the SPOT image and band 5 of the Landsat image (SWIR1) for the northern mixed prairie is between bare soil and crested wheatgrass because the moisture status of the grasslands are right between them. The SWIR2 band of the Landsat image is also sensitive to moisture condition. Therefore, the reflectance for SWIR2 is the highest for the bare soil and the lowest for the crested wheatgrass. The mixed prairie has a reflectance between these two.

3.6.3 Biological parameters, spectral reflectance, and vegetation indices

A Pearson correlation analysis was run to investigate the empirical relationships between spectral reflectance / vegetation indices, and biological parameters. Parts of the correlation coefficients are shown in Table 3.4. It is clear that different wavelength regions and vegetation indices have different degrees of linear correlation with ground biological parameters. Contrary to common sense for remote sensing of photosynthetically active vegetation, the NIR band is not good for detecting biological parameters in the northern mixed prairie. The correlations between NIR and biophysical variables are relatively low ($r < 0.50$, $P<0.01$). This is primarily induced by the existence of the standing dead materials in the top canopy, under canopy litter, and bare soil which highly suppressed the reflectance in NIR. Other bands have higher correlation with biological parameters. Among them, reflectance of green and red have negative relationships with biological parameters that measure green vegetation growth (e.g. vegetation cover, biomass, and PAI). Reflectance at green and red has the highest correlations with green percentage cover (the sum of grass and forb), which is reasonable because the green cover influences the reflectance at green and red directly through absorption, reflection, and transmittance. Normally, high reflectance corresponds to low vegetation cover. Conversely, reflectance for green and red is positively related to the percentage of bare ground ($r = 0.82$, $P<0.01$). The SWIR band also has negative relationships with PAI and total biomass ($r = -0.67$ and -0.65 respectively, $P<0.01$), which is mainly due to the variation of canopy cover and soil moisture content. Bare soil has lower moisture content while higher proportions of vegetation cover and dead materials have higher moisture contents.

Vegetation indices, such as ATSAVI and NDVI, don't have higher correlations with PAI and percentage cover than reflectance at green and red wavelength regions. This is because they were based on reflectance from red and near infrared bands and there are not necessarily high correlations between NIR and green canopy cover in the mixed prairie due to the existence of large amount of standing dead materials in the canopy. Among these indices, ATSAVI is the best because it takes into account soil background information while dead materials have similar spectral characteristics to the bare soil. However, the correlations between vegetation indices and biomass, especially grass biomass, are not as strong as that of the reflectance from green and red bands. The main reason may be that the vegetation indices are more closely related to the vegetation canopy, while biomass information contains litter, which is accumulated from previous years. Furthermore, ATSAVI was not significantly different from NDVI and other indices ($P>0.05$).

There are very low correlations between Landsat 5 TM based reflectance / vegetation indices and biological parameters (data not shown), which may be explained by the senescence of the vegetation canopy when the image was taken. The senescence deteriorates the correlation.

Results of stepwise linear regressions show that information contained in NDCI, RCI, ATSAVI, and NDVI can be empirically explained by the variation of green cover, bare ground, and grass density (grass density is the division of grass cover and grass biomass) (Table 3.5). This indicates the importance of green vegetation cover, bare ground (perhaps along with litter due to the spectral similarity of litter and bare ground), and grass density in remotely collected data. Beyond that, vegetation indices are also well correlated with single biological parameters.

PAI and vegetation indices

PAI is an important vegetation structural parameter because it defines the area that interacts with solar radiation and provides the remote sensing signal. It is a good biological parameter for the application of satellite remote sensing in the prairie region (Baret *et al*. 1989, Goel and Qin 1994, Carlson and Ripley 1997). PAI is similar to LAI except it includes information of standing dead materials and other parts of the plant, not just the leaves. The LAI-2000

Table 3.4 Correlation coefficients between reflectance, vegetation indices, and biological parameters based on one scene of SPOT image on June 22, 2005. Green cover is the sum of grass cover and forb cover.

	Green	Red	NIR	SWIR	NDVI	ATSAVI	NDMI	NDCI	RCI
PAI	-0.54**	-0.56**	-0.28	**-0.67****	**0.61****	**0.60****	-0.49	0.37	0.36
Green Cover	**-0.78****	**-0.78****	-0.44	-0.45	**0.77****	**0.78****	0.00	**0.87****	**0.88****
Grass cover	**-0.75****	**-0.75****	-0.43	-0.44	**0.73****	**0.74****	0.00	**0.83****	**0.83****
Standing dead cover	**-0.61****	**-0.61****	-0.41	-0.42	0.56**	0.56**	0.00	0.47	0.47
Bare ground	**0.82****	**0.82****	0.54**	0.53**	**-0.74****	**-0.75****	-0.03	-0.02	-0.04
Grass biomass	**-0.62****	**-0.63****	-0.32	**-0.61****	**0.67****	**0.67****	-0.35	0.40	0.40
Shrub biomass	0.01	-0.02	0.17	-0.37	0.18	0.16	**-0.69****	0.04	0.05
Dead biomass	-0.56**	-0.57**	-0.32	**-0.62****	**0.60****	0.59**	-0.37	-0.24	-0.25
Total biomass	-0.45	-0.47	-0.17	**-0.65****	0.57**	0.55**	**-0.60****	0.44	0.43

** Significant at P<0.01 level

Table 3.5 Association among vegetation indices and biological parameters

	Equation	R square	Adjusted R square	Standard error
NDCI	0.35 + 0.004 × Green cover – 0.001 × Bare ground percentage	0.84	0.83	0.016
RCI	0.14 + 0.006 × Green cover + 0.001 × Bare ground percentage	0.83	0.82	0.096
ATSAVI	-0.20 + 0.008 × Green cover – 0.011 × Grass density – 0.001 × Bare ground percentage	0.75	0.72	0.046
NDVI	0.25 + 0.005 × Green cover – 0.006 × Grass density – 0.001 × Bare ground percentage	0.74	0.71	0.025

Grass density is the division of grass cover and grass biomass

measures the difference in light intensity above and below the canopy. Large amounts of standing dead materials in the canopy contributed to the PAI values and therefore decreased its correlation with vegetation indices. There is high correlation between PAI and canopy top cover (grass + forb + shrub + standing dead) (r = 0.73, P<0.01). PAI is moderately correlated with SWIR (r = -0.67, P<0.01), ATSAVI (r = 0.60, P<0.01), and NDVI (r = 0.60, P<0.01) (Table 3.4). In northern mixed grasslands, the amount of standing dead material and litter (cover and biomass) was large (Guo *et al*. 2005, Zhang *et al*. 2005). PAI is highly related to vegetation production and therefore it can be an indicator of soil moisture in the northern mixed prairies due to the important influences of soil moisture on vegetation growth in this semiarid environment (Si 2004, Zhang *et al*. 2005).

It is interesting that ATSAVI, which takes into account soil background information, does not perform better than NDVI. This phenomenon may indicate that in the northern mixed prairie, the influence of the dead materials is so significant that traditionally efficient vegetation indices for PAI measurement are not efficient enough compared with NDVI. Finally, the relationship between SWIR reflectance and PAI is strongest using an exponential model (Figure 3.2). SWIR can explain about 42% of variation in PAI. The coefficient of determination (r^2) decreases to 0.41 after the validation. There are no significant correlations between cover indices and PAI, probably due to influences of standing dead materials.

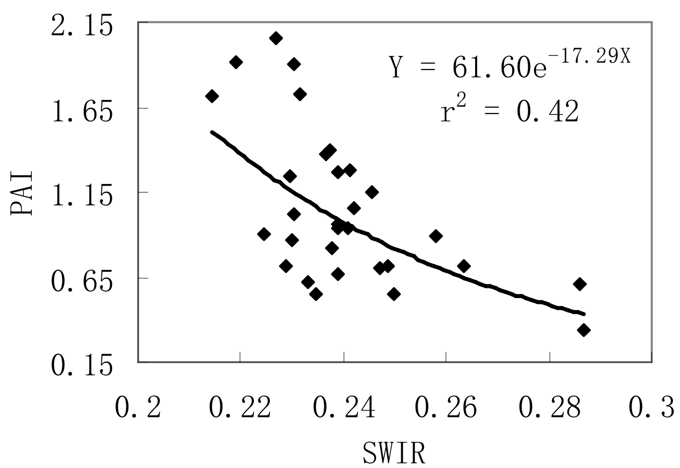


Figure 3.2 Relationships between reflectance of SWIR and PAI based on the SPOT image.

Biomass and vegetation indices

Vegetation indices, specifically ATSAVI and NDVI, are significantly correlated with grass biomass. These two indices can explain approximately 45% of the variation in grass biomass (Figure 3.3). The value decreases to 43% after the cross validation. The SWIR band also has negative correlation with total biomass ($r = -0.64$, $P<0.01$) (Table 3.4), which can be explained by the variation of moisture conditions in different canopies. Vegetation canopies with high biomass tend to have high canopy moisture and large amount of dead materials. Similarly, sites with large amount of dead materials have high soil moisture due to litter's role of keeping soil moisture. Consequently, the variation of biomass is indirectly captured by the SWIR band.

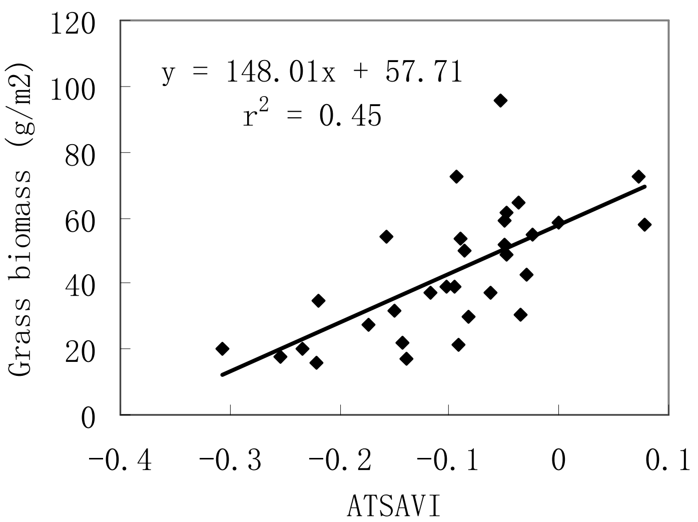


Figure 3.3. Grass biomass and ATSAVI based on the SPOT image. A linear regression can be used to model the relationship between them.

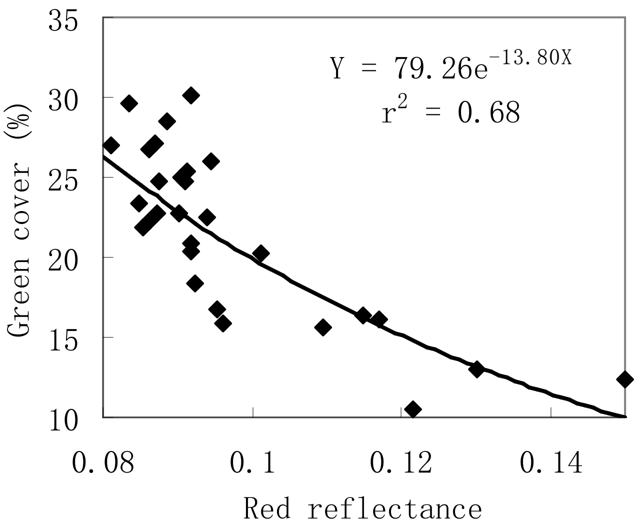
Green cover, reflectance, and vegetation indices

Green vegetation cover, the sum of grass and forb cover, is an important indicator of grasslands health. Its variation may indicate over grazing, soil erosion, and drought condition. Green and red reflectance is negatively correlated with green cover ($r = -0.78$, $P<0.01$). Traditional vegetation indices, e.g., NDVI and ATSAVI have positive correlations ($r = 0.77$-0.78, $P<0.01$) with ATSAVI being the highest among these two vegetation indices (Table 3.4). High green vegetation cover will absorb more incident red light and result in low red reflectance. Lower vegetation canopy with bare ground will reflect more green and red light. Relationships between red reflectance and vegetation cover can be described using a power model (Figure 3.4). Red and green (not shown) reflectance can explain 69% of the variation. The value drops to 67% when validation is applied. To my expectation, RCI and NDCI are promising for detecting ground green canopy information. RCI has a linear relationship with green cover and can explain about 77.0% of the green canopy variation, the largest value (Figure 3.4). The ability of the SWIR band in detecting the change in moisture condition makes it stronger at extracting biomass information than traditional vegetation indices and green and red reflectance (Table 3.4).

Bare ground and reflectance

Grazing, especially over grazing, will absolutely change the percentage of bare ground. As another important indicator of grasslands health, the percentage of bare ground can be detected through reflectance and vegetation indices. Green, red, NDVI, and ATSAVI have high correlation with the percentage of bare ground ($r>0.7$, $P<0.01$) (Table 3.4). A linear regression was conducted for green reflectance and the percentage of bare ground, and results show that green reflectance can explain about 67.0% of the variation. The number dropped to

65.8% after cross validation. However, due to the reason that bare soil or bare ground is mainly distributed in valley and slope grassland, most of the sampling sites for bare ground cluster in the low end of the plot. It indicates that the detection of bare soil may need a sampling scheme different from that of the green vegetation canopy.



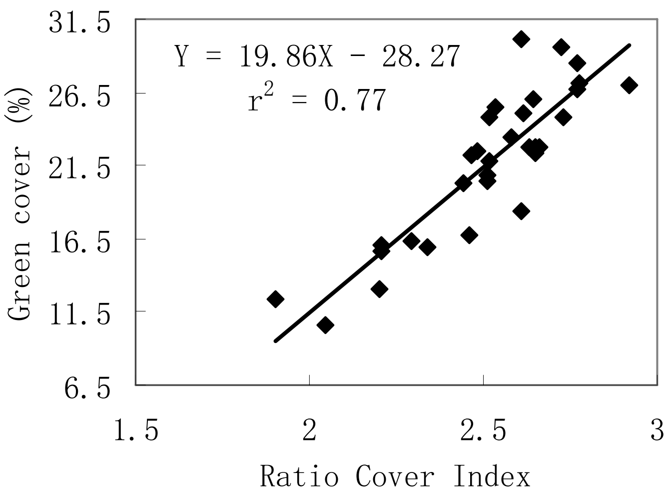


Figure 3.4. Relationships between green cover (grass plus forb cover), red reflectance, and Ratio Cover Index based on the SPOT image. Green cover is the sum of grass and forb cover. Ratio cover index is better at detecting green cover than red reflectance by increasing r^2 value

up to 13%.

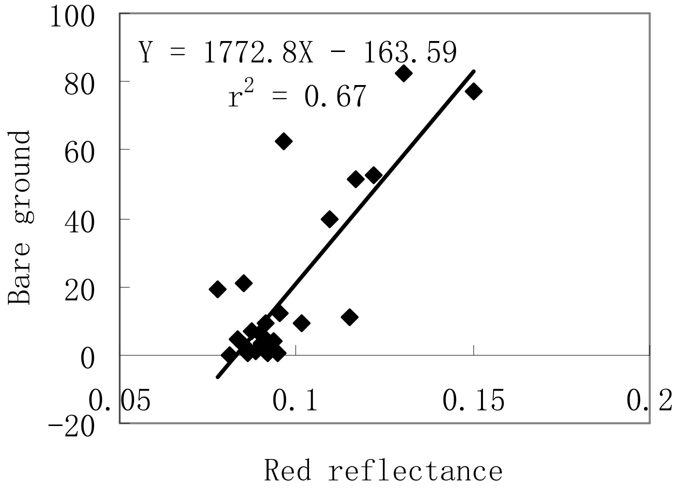


Figure 3.5 The relationship between bareground and green reflectance

3.7 Discussion

For the mixed prairie in Canada, standing dead materials, litter, biological crust, and bare ground constitute the gaps in the vegetation canopy. Litter, along with biological crust and shadow, present a serious problem to the interpretation of VIs (Van Leeuwen and Huete 1996). Influences from this specific background are so high that the spectral curve for the mixed prairie is similar to that of the bare soil, with lower reflectance values than that of bare soil at each band. As a result, NIR reflectance has low correlation with biological parameters. Standing dead materials in the green canopy and the background information tend to decrease the contrast between red and near infrared bands (by lowering the reflectance in near infrared and increasing the reflectance in the red band), thus decreasing the NDVI values. Therefore, traditionally efficient vegetation indices, e.g., NDVI, SAVI, and MSAVI2, might not be as efficient as they are for other vegetation ecosystems. Among them, ATSAVI, which takes the bare soil factor into account, performs better than other vegetation indices listed in this study. However, there are no significant differences between ATSAVI and NDVI, which proves that a soil adjusted vegetation index is not very good for a litter dominated ecosystem.

However, other bands can provide good estimation of the vegetation canopy and its background. Reflectance values from green and red can be used directly to monitor the changes in bare ground, vegetation cover, and biomass. SWIR bands are also highly correlated with biological parameters. Therefore, it is promising that new indices combining these bands might be used to detect the sparse vegetation. For the purpose of detecting biological parameters, considering the possible influences of haze and other atmospheric factors to the green band, the emphasis should be laid on red and SWIR bands. While reflectance at the red band indicates the amount of green cover and possibly the amount of standing dead materials, reflectance at SWIR indicates canopy and soil moisture. By combining these two bands, RCI and NDCI increase the correlation coefficients with green cover from -0.78 to 0.88 and 0.87 ($P<0.01$) respectively, compared to the relationship between red reflectance and green cover. This means that the combination of these two bands probably removes noise for each band, which is also the hypothesis for NDVI. However, these new indices do not have high correlations with other biological parameters. Further validation should be conducted for the next few years to test these new indices and possibly to make new indices to accommodate for the unique background of the northern mixed prairie.

Similarly there is high correlation between NDMI and shrub biomass (Table 3.4). This phenomenon indicates that NDMI also has the ability to detect the vegetation canopy through the detection of canopy moisture. However, the field work was not specifically designed to study shrub communities. The correlation coefficient dropped to 0.59 ($P<0.01$) when a site dominated with shrub was removed. Therefore, it is also possible that we can use NDMI to study the shrub communities after we combine more sites with shrubs.

Results of spectral unmixing show that it is possible to discriminate information in one pixel to some endmembers such as bare ground, grass, and litter. Though grass, bare ground, and litter are underestimated by 13.0%, 15.5%, and 37.3% respectively, endmembers are highly correlated with ground collected biological parameters (Table 3.6). Litter and background have the highest correlation with endmember 1 background ($r = 0.78$, $p<0.01$). The main reason that there are some discrepancies between ground measured cover and calculated cover may be that only 3 endmembers were used. Therefore, more endmembers should be used considering the characteristics of the mixed prairie.

Furthermore, plant litter can be discriminated from soils using the cellulose-lignin absorption feature in the SWIR wavelength (Nagler *et al.* 2000). A Litter-corrected ATSAVI based on ground collected hyperspectral data (using extra reflectance data from 2.0 to 2.2 μm) has been shown to be efficient at detecting biological information in the northern mixed prairie (He *et al*. 2006). Therefore, images from hyperspectral satellite sensors, such as Earth Observing 1 (EO-1) Hyperion (with 220 spectral bands ranging from 0.4 to 2.5 μm), will be considered as the main data for future studies.

3.8 Conclusions

The sparse canopy in the northern mixed prairie is challenging for satellite remote sensing

Table 3.6 Correlation coefficients between endmembers and biological parameters. Endmember 1 to 3 are bare ground, grass, and litter respectively.

	Endmember1	Endmember2	Endmember3
Green cover	-0.77**	0.61**	0.65**
Grass	-0.72**	0.58**	0.59**
Standing dead	-0.63**	0.47	0.50
Litter and Bareground	0.78**	-0.56**	-0.65**

** Significant at P<0.01 level,

because of the accumulation of dead materials in the canopy and the biological crust on the ground. Results of this study show that the spectral curve of the vegetation canopy is midway between the spectral curve for bare soil and green healthy vegetation. This may be mainly explained by the dead materials and biological crust in and under the vegetation canopy. In spite of this, Pearson's correlation analyses indicated that it is still possible to extract information of biological variables about the northern mixed prairie by using reflectance from green, red, SWIR, and vegetation indices. As a preliminary step towards monitoring grasslands health, it is found that different vegetation indices are good at detecting different biological parameters and some empirical relationships have been set up between reflectance, vegetation indices, and biological parameters. While green and red are highly related to the percentage of bare ground and green cover, the SWIR band is highly correlated with PAI due to the influences of litter on soil moisture. Vegetation indices, e.g., ATASAVI and NDVI, can be applied to measure biomass. Furthermore, two new cover indices, RCI and NDCI, which combine SWIR and red bands, can be efficiently applied to detect green vegetation cover. These two indices can explain about 77% of the variation in green cover.

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CHAPTER 4 - APPLICATION OF RADARSAT IMAGERY TO GRASSLAND BIOLOGICAL HETEROGENEITY ASSESSMENT

4.1 Abstract

Heterogeneity, the degree of dissimilarity, is one of the most important and widely applicable concepts in ecology. It is highly related to ecosystem conditions and wildlife habitat. In this study, the feasibility of applying Radarsat-1 HH polarization Synthetic Aperture Radar (SAR) imagery to heterogeneity studies is tested at the Grasslands National Park (GNP) and surrounding pastures in Saskatchewan, Canada. A Radarsat-1 HH standard mode image acquired on August 7, 2003 was complemented by fieldwork in June and July 2003. Height heterogeneity index, Shannon's index, and standard deviation of biological parameters were calculated based on field data. Parameters from texture analysis and standard deviation of the backscatter were correlated with biological parameters to measure grasslands biological heterogeneity. Results showed that different parameters had various abilities to detect field heterogeneity. Grey level co-occurrence matrix mean, correlation, dissimilarity, and contrast showed the ability to detect the variation of grass biomass and total biomass.

Key words: Heterogeneity, Radarsat, Synthetic aperture radar (SAR), Grasslands National Park, Texture analysis

4.2 Introduction

Heterogeneity, the degree of dissimilarity, is one of the most important and widely applicable concepts in ecology (Armesto *et al.* 1991). A higher degree of heterogeneity in ecological systems is supposed to correlate with higher ecosystem stability (Tilman and Downing 1994). Grassland has been described as inherently heterogeneous because their composition and productivity are highly variable across multiple scales (Ludwig and Tongway 1995). Much of the mixed prairie in North America has been transformed to cultivated land or ranches since the late 19th century (Lauenroth *et al.* 1994). The original mixed prairie plant community, disturbed by bison and fire, had different secondary successions, which influenced its heterogeneity status. Therefore, Grasslands National Park of Canada (GNP) was established to preserve northern mixed prairie biodiversity (or heterogeneity). Influences of cattle grazing on grassland ecosystems include removal of vegetation, redistribution of nutrients, dispersal of exotic plant species, and pathogens (Kauffman and Pyke 2001). The enclosure of cattle grazing might produce important impacts on the northern mixed prairie ecosystem and its heterogeneity. Therefore, it is important to investigate grassland heterogeneity for the purpose of grazing management and wildlife habitat protection.

Optical remote sensing has long been applied to study vegetation heterogeneity (Briggs and Nellis 1991, Lauver 1997, Zhang *et al*. 2005). However, the low availability during the growing season because of cloud-cover (Browns *et al.* 1984) makes it difficult to apply optical remote sensing for the northern mixed prairie. Synthetic Aperture Radar (SAR) images can be used as an alternative for optical remote sensing in northern mixed prairie because of its sensitivity to soil moisture and topography (Kasischke *et al.*, 1997; Goyal *et al.*, 1999; Hill *et al.*, 2000; Bindlish and Barros, 2001) and its ability to penetrate through cloud cover. Goyal *et al*. (1999), Hill *et al*. (1999 and 2000) and Buckley (2004) applied SAR images to the study of grassland ecosystems, but none of those studies attempted to investigate the biological heterogeneity of grassland. Therefore, the objective of this study is to test the feasibility of using a HH polarized Radarsat-1 image to measure the biological heterogeneity of a northern mixed prairie.

4.3 Study Area

The study area includes Grasslands National Park (GNP) (49° N, 107° W) and surrounding pastures, located in southern Saskatchewan along the Canada - United States border. This area falls within the mixed prairie ecosystem (Coupland 1992). The park is approximately 906.5 km^2 in area but in two discontinuous blocks, west and east. The first land was acquired for the park in 1984; hence, some areas of the park have been under protection from livestock grazing for over 20 years. The park area consists of upland and valley grasslands. The dominant plant community in the upland grasslands is needle-and-thread – blue-grama-grass (*Stipa-Bouteloua*), which covers nearly two thirds of the park's ground area. The dominant species in this community include needle-and-thread (*Stipa comata Trin. & Rupr*), blue grama grass (*Bouteloua gracilis (HBK*) *Lang. ex Steud*.), and western wheatgrass (*Agropyron smithii Rydb.*) (Fargey *et al*. 2000). The GNP area has a mean annual temperature of 3.8 °C and a total annual precipitation of 325 mm (Environment Canada 2003). Approximately half of the precipitation is received as rain during the growing season.

4.4 Materials and Methods

4.4.1 Field work

Ten stratified sites were randomly selected in the upland grasslands within the park and in surrounding pastures within 20 km of the park (Figure 4.1). Field work was conducted in June and July of 2003. Three 100x100 m plots were set up in each site. Each plot was composed of two 100 m perpendicular transects intersecting at the centre in north-south and east-west directions. These two transects were meant to capture the variation within a plot. Twenty-one quadrats (20x50 cm) were placed in each transect at 10 m intervals. Percent cover of grass, forb, shrub, standing dead grass, litter, moss, lichen, and bare ground as well as species composition was collected at each quadrat. Above ground biomass ("biomass" hereafter) was collected at 20 m intervals using a harvesting method. Clipped fresh biomass was sorted into four groups; grass, forb, shrub, and dead materials. They were then dried in the oven for 48 hours at 60 ℃. Canopy moisture was calculated from the difference of dry biomass and fresh biomass. Leaf Area Index (LAI) was measured using a LiCor LAI-2000 Plant Canopy Analyzer (LI-Cor, Inc., Lincoln, Nebraska).

Field collected data were processed using descriptive statistics and diversity indices. The selection of heterogeneity indices was based on the literature, from which typical indices that can be used to indicate vegetation canopy structure were chosen. Biological parameters were integrated for each site by averaging quadrat values. Standard Deviation (SD) and Coefficient of Variation (CV) were used to measure the variation of biological parameters within sites. Shannon's index (Rosenzweig, 1995) and Heterogeneity Index of Height (HIH) (Wiens, 1974) were also calculated to represent species diversity and the variation of canopy height inside sites respectively (Table 4.1).

Table 4.1. Grassland heterogeneity indices and their formulas as used in the thesis

Index	Equation	Notes
Shannon's index	$-\sum p_i \ln(p_i)$	p_i is the proportion of the total number of individuals occurring in species i
Heterogeneity index of height	$\frac{\sum (Max - Min)}{\sum \bar{x}}$	Max=maximum value of the canopy height within quadrats, Min=minimum value of the canopy height within quadrats, $\bar{x}$ is the mean value of canopy height in a quadrat

4.4.2 Image analysis

One standard mode Radarsat -1 image with HH polarization was acquired for this study (Figure 4.1). The image was taken on August 7, 2004 and has a pixel spacing of 12.5 m. Digital numbers were converted to backscatter (db) and a Gamma filter was applied to remove speckle before the conversion using PCI Geomatica^{TM} software (PCI Geomatics, Richmond Hill, Ont.). The image was then registered to a Universal Transverse Mercator projection (zone 13) through a geometric correction. A nearest neighbour resampling method was used with 35 ground control points and the root mean square error was 0.35 pixels.

Grey Level Co-occurrence Matrix (GLCM) Texture analysis is a commonly used

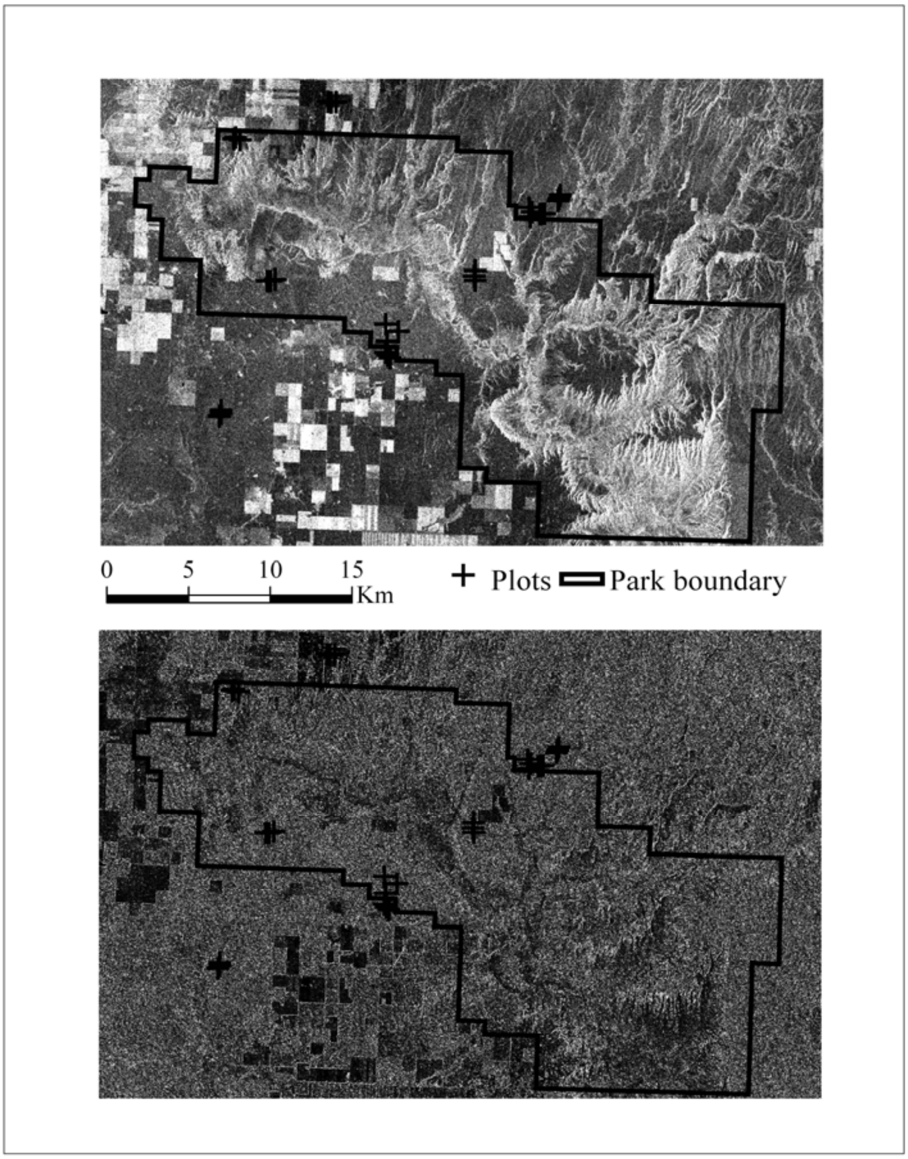


Figure 4.1. Field plots distribution and textural parameters. (a) Radarsat 1 HH polarization image of GNP, August 7, 2003. (b) Result of texture analysis (Contrast).

method for describing localized variation in grey scale. During the process of texture analysis, a GLCM is computed to describe the stochastic properties of spatial distribution of the grey level (Haralick *et al*. 1973, Levine 1985, He and Wang 1990, Baraldi and Parmiggiani 1995, Hall-Beyer 2000). Various measures, including energy (uniformity), contrast (contrast of grey scales), and entropy (disorder), are then calculated from the GLCM. Results of textural analysis can be used to describe the heterogeneity within a landscape (Briggs and Nellis 1991). Energy, contrast, and entropy have been used as indicators of heterogeneity or local variance (Woodcock and Strahler 1987, Briggs and Nellis 1991, Anys and He 1995). Other texture parameters, such as homogeneity and correlation, can be also applied in heterogeneity studies due to their ability to indicate homogeneity or heterogeneity.

Texture analysis was applied to the HH polarization image with a window size of 9 x 9 pixels (Hill *et al*. 2000). Eight measures of texture analysis − i.e., contrast, homogeneity, dissimilarity, energy, entropy, mean, standard deviation, and correlation − were calculated from the GLCM or GLDV using PCI Geomatica™ software (In Figure 4.1, a contrast image was shown because of its ability to demonstrate variation). A 7x7 window, which is approximately the same size of the plots, was used to export textural parameters and to correlate with field variation**.** Mean values of textural parameters within the windows were used to indicate imagery heterogeneity (grey level variation of pixels in the RADARSAT image). Analysis of variance (ANOVA) was used to test if the biological heterogeneity between grazed and protected sites was statistically different. The relationships between standard deviation of biological parameters in field plots and mean values of textural parameters in corresponding windows were first analyzed through Pearson correlation. Linear regression was then applied to determine the prediction ability of field heterogeneity (standard deviation of biological parameters) by image heterogeneity. Results were validated using the Jack-Knife cross validation method, which withdraws one sample each iteration and runs the model n-1 iterations.

4.5 Results and Discussion

4.5.1 Biological parameters and field heterogeneity

There are no significant differences between grazed sites and protected sites except that variation of dead materials in the protected sites was higher than in the grazed sites ($P<0.05$) (Table 4.2). This can be explained by different speeds of dead material accumulation in transects of the protected sites. With the removal of grazing cattle, the speed of dead material accumulation is high at the bottom and low at the top of the hill. As a result, there was a larger variation in protected sites. Having been protected for the longest time, sites U1 and U2 had the highest variation specifically. Transects along gradients with changing vegetation species, cover, biomass, and density provided detailed information of the change of biological parameters. There was low biomass and low grass cover at the top of the hill. An increase in biomass and grass cover from the top to the bottom of the hill (depressions) was observed. Furthermore, different parameters showed various degrees of heterogeneity, with forbs showing the highest variation because of the small percentage of forb biomass to total biomass; the small amount is likely to result in high variation. Among all sites, G1 (a site in grazed prairie) had the lowest degree of heterogeneity for all variables, which can be explained by the low fluctuations of elevation,(average slope of 2.5^o) homogeneous soil moisture (CV of soil moisture was 6.1% from the soil moisture data collected in 2004, among the lowest for all sites) and canopy moisture. In northern mixed prairie, flat areas with homogeneous soil moisture have a low level of heterogeneity due to the critical role of soil moisture in vegetation growth (Kravchenko *et al*. 2000, Zeleke and Si 2004, Si and Farrell 2004).

Table 4.2. Field biological heterogeneity. Shannon's index was calculated on species cover, and HIH was calculated on canopy height. G and U stand for grazed and ungrazed respectively.

Site	Grass biomass (g/m^2)	Forb biomass (g/m^2)	Dead materials (g/m^2)	Total biomass (g/m^2)	Canopy moisture (g/m^2)	HIH	Shannon's Index
G0	55.2	24.8	58.1	104.8	74.4	1.33	2.11
G1	28.8	15.1	30.2	54.0	34.5	1.33	1.93
G2	60.2	19.9	48.6	100.8	113.2	1.41	2.01
G3	40.0	36.4	45.3	79.2	109.6	0.98	1.85
G4	49.9	15.7	59.4	99.5	62.1	1.28	2.30
U0	65.7	28.6	62.6	115.1	93.8	1.6	2.31
U1	43.5	19.9	111.6	143.3	126.1	1.46	1.97
U2	76.8	21.9	125.4	186.5	169.2	1.59	2.29
U3	56.3	23.3	59.7	106.7	107.8	1.06	2.31
U4	52.8	22.9	65.7	111.2	52.3	1.2	2.22
Mean	52.9	22.9	66.7	110.1	94.3	1.32	2.13

4.5.2 SAR image heterogeneity

There were no significant differences for backscatter and texture parameters between grazed and protected sites (Table 4.3). Heterogeneity variables derived from the SAR image with the texture analysis indicated a high degree of heterogeneity for the study area except one site

(G1), which also showed the lowest variation based on field measurements. G1 had much lower heterogeneity values and higher homogeneity values. The gap between G1 and other sites is larger than measured field heterogeneity, --especially for contrast, dissimilarity, mean, SD, and entropy, --which could be explained by the low fluctuations of elevation as well as soil moisture and canopy moisture. Soil moisture and canopy moisture influence Radarsat backscatter through soil dielectric constant (Hill *et al.* 2000) and as a result homogeneous soil moisture results in homogeneous backscatters.

Table 4.3 Imagery heterogeneity by textural parameters. G and U stand for grazed and ungrazed sites respectively.

Site	Backs-catter	Homo-geneity	Contrast	Energy	Dissimi-Larity	Mean	SD	Entropy	Corre-lation
G0	1.38	0.18	32.20	0.01	4.64	13.93	5.69	4.57	0.48
G1	1.39	0.85	0.71	0.57	0.36	0.29	0.65	1.07	0.24
G2	1.56	0.21	29.67	0.01	4.28	9.66	5.87	4.51	0.55
G3	1.39	0.23	26.94	0.01	3.96	12.15	5.76	4.48	0.60
G4	1.42	0.22	27.50	0.01	4.09	10.2	5.63	4.45	0.56
U0	1.39	0.19	30.81	0.01	4.41	13.64	5.69	4.56	0.52
U1	1.35	0.21	24.73	0.01	4.01	10.67	5.72	4.48	0.60
U2	1.22	0.22	24.51	0.01	3.89	15.64	5.03	4.45	0.51
U3	1.44	0.21	28.24	0.01	4.16	10.74	5.6	4.49	0.54
U4	1.05	0.23	24.65	0.01	3.94	11.06	4.72	4.44	0.44
Mean	1.36	0.28	25.00	0.07	3.77	10.80	5.04	4.15	0.50

4.5.3 Modeling field level heterogeneity with RADARSAT imagery heterogeneity

There were low correlations between field biological heterogeneity and imagery heterogeneity (Table 4.4). However, several textural parameters had significant relationships with field biological heterogeneity. The correlation coefficients (r) between mean and grass biomass and total biomass are 0.77 and 0.70 respectively. Contrast, entropy, and dissimilarity were moderately correlated with the variation of grass biomass (r ranges from 0.62 to 0.64)). GLCM correlation was also positively correlated with grass cover with a correlation coefficient of 0.64 and GLCM homogeneity was correlated grass biomass with a correlation coefficient of -0.64. Canopy moisture moderately correlated with mean and correlation, which coincided with my expectation. One interesting result is that contrast, mean, dissimilarity, and entropy were negatively correlated with the variation of the standing dead cover and homogeneity was positively correlated with standing dead cover variation. The reason for these correlations is that the standing dead materials may not influence SAR backscatter as strongly as other parameters. Consequently, these relationships can be examined with linear regression (Figure 4.2). The GLCM mean can explain 59% of variation of grass biomass and 49% of total biomass variation. The numbers decreased to 54% and 43% when validation was applied. Furthermore, the combination of different field biological heterogeneity parameters helps to explain the variation of textural parameters (Mean = -7.6 + 0.22 x Grass biomas + 0.3 x Forb biomas, $r^2 = 0.79$), which indicates that forb also contributes to the imagery variation.

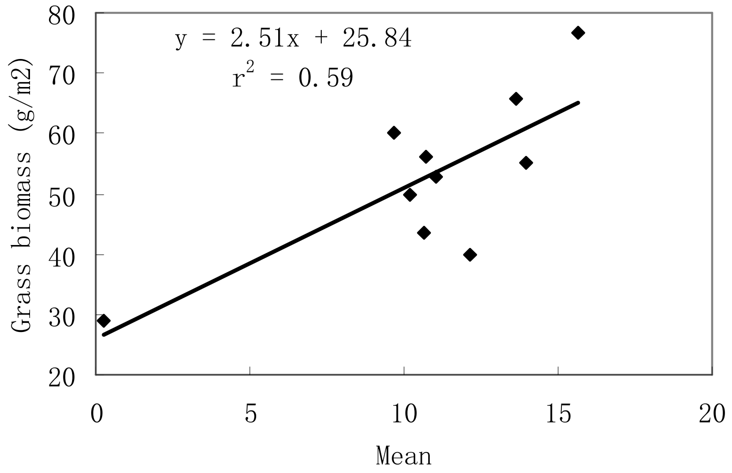
The sparse canopies with low herbage production do not contribute much to backscatter in the upland region of mixed grass prairie (Hill *et al*. 2000). There were no significant correlations between the image heterogeneity variables and Shannon’s index or HIH, which proves from another aspect that radar backscatter (C band) with HH polarization can not detect vegetation canopy variation directly. Backscatter is most probably influenced by soil and geological parameters in *Stipa-Bouteloua* grasslands (Hill *et al*. 2000). Therefore, image heterogeneity is more likely to be the result of landscape heterogeneity.

Table 4.4 Correlation coefficients between field level heterogeneity and image level heterogeneity. There are significant correlations between grass biomass, standing dead cover, and textural parameters.

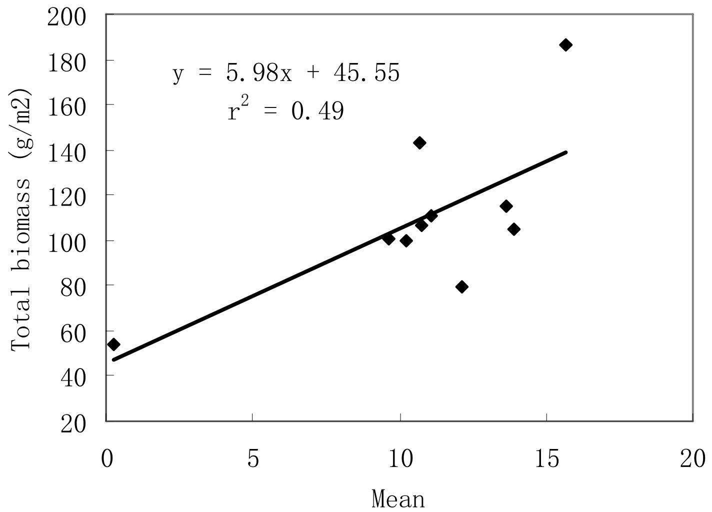
	Back-scatter	Homo-geneity	Contrast	Dissimi-larity	Mean	Entropy	Corre-lation
Grass Biomass	-0.14	-0.64*	0.62*	0.64*	0.77**	0.63*	0.37
Forb Biomass	-0.06	-0.44	0.46	0.44	0.54	0.45	0.43
Dead Biomass	-0.41	-0.42	0.25	0.35	0.56	0.42	0.39
Total Biomass	-0.38	-0.55	0.41	0.49	0.70*	0.55	0.43
Grass & Forb Cover	0.53	-0.24	0.21	0.20	0.21	0.26	0.64*
Grass Cover	0.48	-0.34	0.30	0.33	0.11	0.33	0.64*
Forb Cover	0.22	-0.33	0.45	0.37	0.36	0.33	0.26
Standing Dead Cover	-0.03	0.64*	-0.69*	-0.65*	-0.62*	-0.65*	-0.51
Canopy moisture	0.07	-0.52	0.43	0.47	0.63*	0.53	0.62*
Shannon’s index	-0.06	-0.31	0.39	0.35	0.26	0.32	0.17
HIH	-0.03	-0.02	0.01	0.03	0.19	0.00	-0.07

** Significant at the 0.01 level; * significant at the 0.05 level.

However, we did find that canopy moisture moderately correlated with the variation of Radarsat backscatter, which indicates that vegetation canopy probably contributes to the variation of backscatter. Among parameters influencing backscatter, soil moisture significantly influences radar backscatter from the mixed prairie, and changes in the water content of soils and vegetation can cause large variations in radar backscatter (Hill *et al.* 1999). Soil moisture, the key factor of vegetation growth in a semi-arid environment, is determined by topographical parameters such as slope and upslope length (Zeleke and Si 2004). Therefore, vegetation growth is controlled by topography through the key role of soil moisture (He et al. 2006). The influences of topography on the vegetation community are so



(a)



(b)

Figure 4.2. Field heterogeneity prediction models based on imagery heterogeneity, (a) grass biomass and mean, (b) total biomass and mean.

important that Rey-Benayas and Pope (1995) even used a topographic index to stand for biological heterogeneity (vegetation richness). The more uniform the landscape, the lower the variation. Stated simply, biological heterogeneity is positively correlated with landscape heterogeneity (Burnett *et al.* 1998) where topography and soil moisture are important components. Radarsat image plus texture analysis provide one way to measure landscape heterogeneity through the measurement of soil moisture. Therefore, we can conclude that heterogeneity measured from textural parameters of the Radarsat image indirectly showed field vegetation variation.

4.6 Conclusions

There are no significant differences for biological heterogeneity between grazed and protected sites. However, it is feasible to use Radarsat images to detect field biological heterogeneity through landscape heterogeneity. Textural measurements can be applied to detect field biological heterogeneity. Certain parameters, including mean, correlation, dissimilarity, and contrast, could be used to predict heterogeneity of grass biomass, total biomass, and grass cover. About 43% to 54% of field biological heterogeneity can be estimated using Radarsat-1 SAR data through texture analysis among which the variations of soil moisture, canopy moisture and topography can be key factors.

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CHAPTER 5 - MONITORING TEMPORAL HETEROGENEITY IN A PROTECTED MIXED PRAIRIE ECOSYSTEM USING 10-DAY NDVI COMPOSITE

5.1 Abstract

The northern mixed prairie has the distinctive characteristics of sparse vegetation canopy, the existence of biological crust, and accumulation of dead materials. This paper applied coarse resolution imagery to study seasonal and annual changes of net primary productivity (NPP) in the northern mixed prairie. Results indicate that apart from their coarse spatial resolution, AVHRR, Normalized Difference Vegetation Index (NDVI), Maximum Value Composites (MVC), and SPOT Vegetation NDVI MVC can show the seasonal and annual NPP variation. The variation is moderately correlated to temperature and precipitation. This study also validates that Standardized Precipitation Index is a useful indicator of soil moisture condition for the northern mixed prairie and that NPP in June is highly correlated with soil moisture in May, with early season precipitation playing an important role for annual NPP. Trend line analysis indicates that the removal of grazing cattle has multiple influences on the grasslands ecosystem. Though NPP for most of the area is quite stable, protection has increased the accumulation of dead materials in some of the upland grassland and increased vegetation cover in the valley grassland. Further investigation of the change in the biological heterogeneity in the park indicates that spatial biological heterogeneity is highly related to weather conditions, with the largest variation right before the full growing season.

Key Words: Net primary productivity, AVHRR, SPOT, maximum value composite, trend analysis, temporal heterogeneity

5.2 Introduction

As a pool of carbon dioxide and a gene pool of wildlife and vegetation, the grasslands of North America are an important component of the global ecosystem (Coupland 1992). Both the government and the public became concerned with grasslands when the original grassland was transformed to cropland and rangeland began to degrade (Lauenroth et al. 1994). As a result, Grasslands National Park (GNP) (49° N, 107° W) was set up to preserve the biodiversity of the mixed prairie in Canada. After about 20 years protection, it is important to evaluate historical variation in the grassland ecosystem by assessing the impacts of protection and climatic variation on grassland net primary production for the purpose of management strategy adjustment.

Temporal heterogeneity of net primary productivity (NPP) is the change of spatial dissimilarity in NPP across time. It is one of the most important and widely applicable ways to study historical variations of vegetation communities (Peet 1974, Armesto *et al.* 1991, West 1993, Southwood and Henderson 2000). By observing temporal heterogeneity, it is possible to identify factors that are important for vegetation growth. There has been a long history of applying satellite remote sensing in studying the historical change of NPP (Weiss *et al.* 2004), with AVHRR Normalized Difference Vegetation Index (NDVI), Maximum Value

Composite (MVC) being the most commonly used imagery due to its high temporal resolution and long historical record (James and Kalluri 1994, Reed *et al.* 1994, Ramsey *et al.* 1995, Townsend *et al.* 1995, Fuller 1998, Yang *et al.* 1998, Senay and Elliot 2000, Guo 2003, Weiss *et al.* 2003).

To study seasonal and annual NPP variation, the first step is to decide the onset and end of the growing season in the year. A threshold value (Lloyd 1990), a moving average method (Reed *et al.* 1994), the largest NDVI increase (Kaduk and Heimann 1996), or series of piecewise logistic functions (Zhang *et al.* 2003) have been applied to decide the time of green-up and senescence. As the second step, a time integrated NDVI to represent NPP during the growing season can be calculated to decrease the data dimensionality. Normally, NDVI integral of the growing season was computed as the integrated NDVI (e.g. Reed *et al.* 1994, Yang *et al.* 1998). For arid and semiarid environments, mean NDVI for the growing season is commonly calculated (Fuller 1998, Rigina and Rasmussen 2003). These NDVI integral or mean NDVI are used to represent NPP (Reed *et al.* 1994, Yang *et al.* 1998, Fuller 1998, Rigina and Rasmussen 2003). Thereafter, methods such as trend line analysis (e.g., Fuller 1998, Rigina and Rasmussen 2003) and Principle Component Analysis (PCA) (Fung and LeDrew 1987, Townshend *et al.* 1987, Eastman and Fulk 1993, Lambin and Strahler 1994, Benedetti *et al.* 1994, Anyamba and Eastman 1996, Hirosawa *et al.* 1996, Young and Anyamba 1999, Piwowar and Millward 2003, Rigina and Rasmussen 2003), can be applied on the NPP/NDVI data to evaluate historical change. Other methods, such as Fourier Transformation (FT) (Anders *et al.*1994, Olsson and Eklundh,1994, Azzali and Menetti 2000) and change vector (Lambin and Strahler 1994, Young and Anyamba 1999), have been proven to be useful for vegetation classification purposes but further development is necessary to be used in time series studies (Rigina and Rasmussen 2003).

To date, no studies have been conducted to detect annual change of NPP in the northern mixed prairie. Therefore, objectives of this study are to 1) monitor the seasonal variation in the mixed prairie, 2) assess the influences of the removal of grazing cattle on the NPP of northern mixed prairie, 3) evaluate the impacts of climatic variation on NPP, and 4) study temporal heterogeneity of the northern mixed prairie by investigating relationships between climatic variation and spatial variation of NPP.

5.3 Study Area

The study area is the west block of Grasslands National Park (GNP) (49° N, 107° W), located in southern Saskatchewan along the Canada - United States border. This area falls within the mixed prairie ecosystem (Coupland 1992). The first land was acquired for the park in 1984; hence, most areas of the park have been under protection from livestock grazing for about 20 years. The park area consists of upland and valley grasslands. The dominant plant community in the uplands of the mixed grass prairie ecosystem is needle-and-thread – blue grama grass (*Stipa-Bouteloua*), which covers nearly two thirds of the park's ground area. The dominant species in this community include needle-and-thread (*Stipa comata Trin. & Rupr*), blue grama grass (*Bouteloua gracilis (HBK*) *Lang. ex Steud*.), and western wheatgrass (*Agropyron smithii Rydb.*) (Fargey *et al*. 2000). Comparatively, valley grasslands are dominated by western wheatgrass *a*nd northern wheatgrass (*Agropyron dasystachym*), along with higher densities of shrubs and occasional trees. The GNP area has a mean annual temperature of 3.8 ºC and a total annual precipitation of 325mm (Environment Canada 2003). Approximately half of the precipitation is received as rain during the growing season. Common soils in the Park areas are chernozemic soils and solonetzic soils (Fargey *et al*. 2000). Chernozemic soils are the most common in grassland communities, with a dark color and high amount of organic content. Solonetzic soils, with their high salinity and lighter color, are formed due to drought and high evaporation (Michalsky *et al.* 1994). Under the sparse vegetation canopy in the Park area, a large part of surfaces are covered by microphytic communities of small non-vascular plants. These microphytic communities include mainly mosses, lichens and fungi, which form biological crusts over soils and rocks.

5.4 Data

AVHRR NDVI 10-day MVC from 1993 to 1998 and SPOT Vegetation 10-day composite from 1998 to 2004 were obtained for the Park area, which have a spatial resolution of 1 km. The MVC is necessary, especially for the northern mixed prairie, because of the low availability of optical remote sensing imagery due to cloud cover during growing seasons (Browns *et al.* 1984). Only images related to the growing season from April to October were utilized in this study because NDVI time series for the non-growing season are not helpful for phenological separation (Ramsey *et al.* 1995, Senay and Elliott 2000, Weiss *et al.* 2004). The NDVI imagery was reprojected to a UTM projection to overlay with geographical layers, e.g. the Park boundary, the river, and roads for the park area. Meteorological data, including precipitation and temperature, were obtained for Val Marie, the town about 1 km away from the west block of the Park. The weather data were downloaded from Environment Canada's website (Environment Canada 2004).

5.5 Methods

5.5.1 Climatic factors

A 1-month Standardized Precipitation Index (SPI) was calculated to indicate the soil moisture condition based on precipitation data. The index was originally developed to define and monitor drought condition (McKee *et al.* 1993, McKee *et al.* 1995, Ji and Peters 2000). The SPI is calculated by fitting historical precipitation data to a Gamma probability distribution function for a specific time period and location with 0 and 1 as mean and standard deviation respectively (McKee *et al.* 1993, McKee *et al.* 1995, Ji and Peters 2000). According to McKee *et al.* (1995), SPI values can be divided into seven categories: extremely wet (> 2.0), very wet (1.5 to 1.99), moderately wet (1.0 to 1.49), near normal (-0.99 to 0.99), moderately dry (-1.49 to -1.0), severely dry (-1.99 to -1.5), and extremely dry (<-2.0).

A linear regression analysis was run to identify the relationships between NDVI and climatic factors. Prediction models were developed for NDVI and the results were validated with the Jack-Knife cross validation method, which withdraws one sample each iteration and runs the model for (n-1) iterations.

5.5.2 Phenological period decision

The onset and end of the growing season were decided by combining temperature, NDVI values, and the change in slopes of the NDVI curve. The first largest NDVI increase when air temperature is above 5 ºC (Frank and Hofmann 1989) was selected as the green-up period. The largest NDVI drop from above 0.25 to below 0.25 is selected as the end of the growing season. Selection of this value is mainly decided by considering phenological characteristics of the mixed prairie and corresponding changes of the dataset. For years NDVI values are higher than 0.25 even in October, we chose the last rapid drop of NDVI as the end of growing season. Mean NDVI was calculated for each year, to represent annual NPP in the northern mixed prairie, by averaging the NDVI values throughout the growing season.

5.5.3 Historical NDVI changes

A trend analysis was conducted according to Fuller (1998). For every pixel in the image, NDVI was plotted as a function of time and the regression line was subsequently computed. The result was a “slope image” depicting the slope for each pixel's associated trend line. The slope image captures the long trend of NPP change in the grasslands. In order to investigate whether the trends (the slopes) capture the development in the integrated NDVI, areas showing the same trends were identified and compared with the original integrated NDVI.

5.5.4 Spatial and temporal heterogeneity

Standard Deviation (SD) and Coefficient of Variance (CV) are among the most commonly used heterogeneity indicators. Roth (1976) and Wiens (1974) applied CV as the heterogeneity index to measure spatial heterogeneity of grasslands with field data. Guo *et al.* (2003) also applied CV to indicate the change of grassland heterogeneity. These studies showed that CV is a good indicator of grasslands vertical and horizontal structure. In addition, Gould (2000) used standard deviation of NDVI to indicate species diversity based on Landsat 7 image. Therefore, both SD and CV were calculated to measure the variation of NPP in the park. Only SD was shown because both parameters show similar trends with SD having a larger range.

5.5.5 Field validation

To validate phenological change, the canopy reflectance was measured using an ASD FR Pro spectroradiometer (Analytical Spectral Devices, Inc., USA). The measurement range was 350-2500nm, and the spectral resolution was 3 nm from 350 to 1000 nm and 10 nm from 1000 to 2500 nm. The 25^{o} field of view probe was pointed down vertically at the canopy from a height of approximately 1 meter. Measurements were taken between 1000h and 1400h local time on clear days. A white reflectance panel (Labsphere, USA) was used to calibrate the reflectance at approximately 10 minute intervals to minimize the influence of atmospheric condition changes. NDVI was calculated to better detect vegetation signals. Different sites within the park were visited in early May (mainly crested wheatgrass), late June and early July (upland grassland, dominated by needle-and-thread), and early August (one transect from upland to sloped grassland), 2005. Considering the homogeneity of the upland grassland, it is reliable to use these sites to stand for the mixed prairie.

5.6 Results

5.6.1 Variation of NDVI during the full growing season

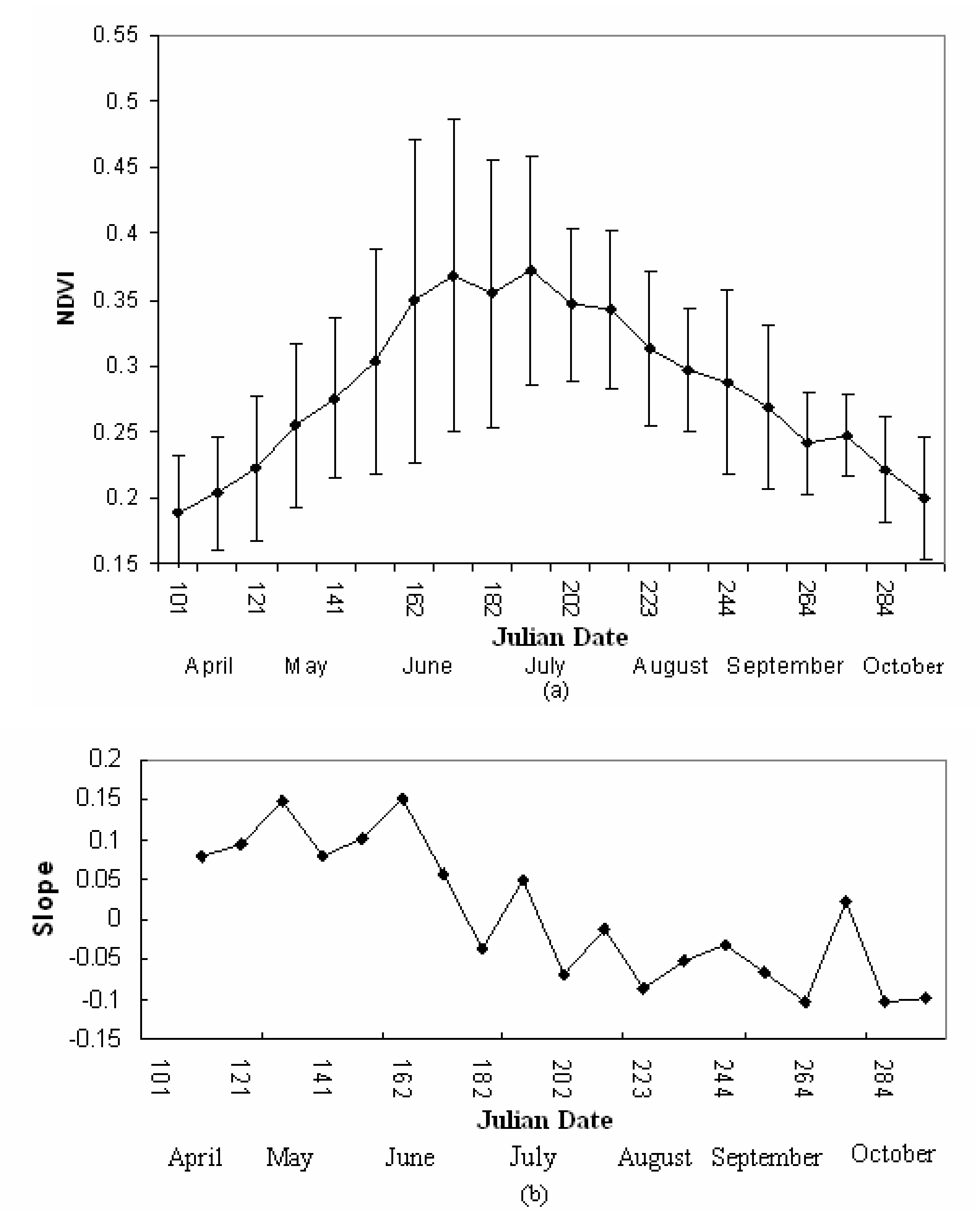

Figure 5.1. Variation of spatially and temporally averaged NDVI (a) and the rate of NDVI change (slope) over (b) the growing season in the GNP from 1993 to 2004. The error bars (standard deviation) show that there are large year to year variations especially for the

maximum growing season.

The northern mixed prairie shows a special seasonal variation (Figure 5.1). NDVI values are around 0.2 in early April − when there are only dead materials, bare soil, and biological crust − as daily average temperature is still below or around 0 ºC. As early as mid April, forb (e.g. Pasture sage (*Artemisia frigida*), Scarlet mallow (*Malvastrum coccineum (Pursh) A. Gray*), Moss phlox (*Phlox hoodii Richards.*), American vetch (*Vicia americana Muhl. var. Americana*), Yarrow (*Achillea millefolium L.*)), and shrub species [e.g., silver sagebrush (*Artemisia cana*), buckbrush *(Symphoricarpos occidentalis)*, and Rabbit brush (*Chrysothamnus nauseosus*)] start green-up, which can be seen from the gradual increase of NDVI from April 11th to April 20th (Julian day 101-110). Due to the reason that these species are not the dominant species in the mixed prairie, their green-up is not very obvious; this increase may also be due to the change in soil moisture.

Then, there are two large NDVI increases (large slope in the NDVI curves) before and in the early growing season. The first increase from May 1st to May 10th (Julian day 121 to 131) corresponds with the widely green-up of forb and shrub species plus crested wheatgrass (*Agropyron cristatium*). The second increase from June 1st to June 11th (Julian day 152 -162) indicates the wide growth of native grass species (e.g., needle-and-thread, western wheatgrass, and June grass (*Koeleria macrantha* (Ledeb.) J.A. Schultes f.). Then NDVI values reach the first peak (around 0.35) in late June (Julian day 172 - 182), which is corresponding with the rapid growth of native grass species (e.g., needle-and-thread, western wheatgrass, and June grass) after precipitation in the early growing season in the northern mixed prairie. Due to the background influence, their green-up is represented by the gradual increase of NDVI between the two rapid increases. There are two peak NDVI values during the growing season, one in June and one in July, corresponding with the appearance of the full growing season in the northern mixed prairie at distinct times. During this 12 year period, NDVI maxima appeared six times in June, four times in July, and one time in August (no data for 1994). Therefore, in an average graph, two NDVI peaks are shown for June and July.

After the full growing season, the process of senescence can be seen clearly from the decreasing NDVI values from late July (native grass species) to late October (some shrub and forb species such as silver sagebrush). There are three rapid drops, July 11th to July 21st (Julian day 192-202), August 1st to August 10th (Julian day 213-223), and September 11th to September 20th (Julian day 254-264), which primarily correspond to the senescence of grass, forb and shrub species. Thereafter, NDVI remains stable at around 0.23 because only dead materials, bare soil, and biological crust remain. NDVI values then drop rapidly in October (Julian day 274) with the start of winter and the appearance of snow.

5.6.2 Seasonal variation of NDVI, precipitation, SPI, and temperature

Temperature and precipitation show strong yearly cyclic variation for the past 12 years (Figure 5.2). Average temperature (1937-2004) for May, June, July, and August are 11ºC, 15.8ºC, 18.3ºC, and 17.7ºC respectively, with July being the highest. Compared with temperature, precipitation values show a similar trend but with larger variations. Average precipitation values for May, June, July, and August are 39.4, 64.3, 46.0, and 30.7 mm respectively, with June and July (the full growing season) being the highest. However, compared with the general one peak temperature in July for each year, the variation of precipitation is much larger. Ranges of precipitation (Maximum minus minimum) for May, June, and July are 122.2, 144.4, and 162.0 mm respectively and the highest amount of monthly precipitation for each year can appear in any month from May to September.

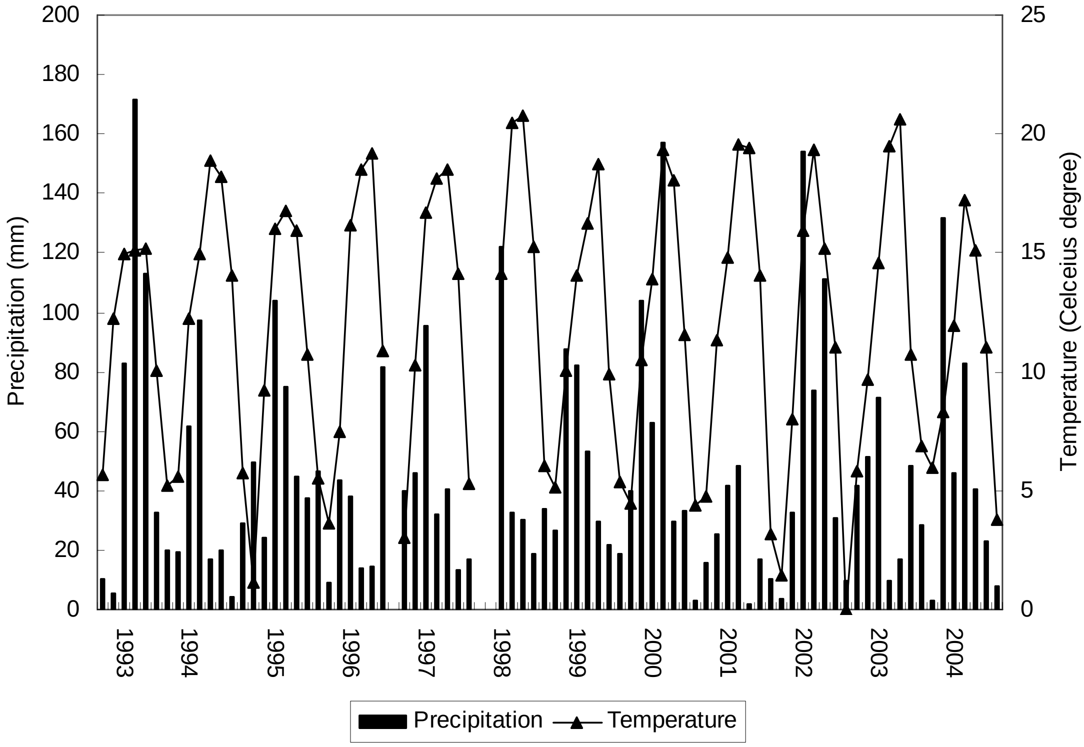

Figure 5.2. Monthly temperature and precipitation from April to October. Temperature data for May 1998 are missing. Precipitation data for April and May, 1998 are missing.

Variations of SPI are highly corresponding with NDVI (Figure 5.3). Generally high SPI corresponds with high NDVI before the late growing season. Based on the SPI of the growing season (May, June, and July), it is evident that years 1993, 2000, 2002, and 2004 are wet years and 1996, 2001, and 2003 are dry years. Corresponding to the variations of temperature and precipitation, NDVI also shows a similar trend highly influenced by soil moisture conditions (Figure 5.3). NDVI values are low for 1995, 2001, and 2003 and are high

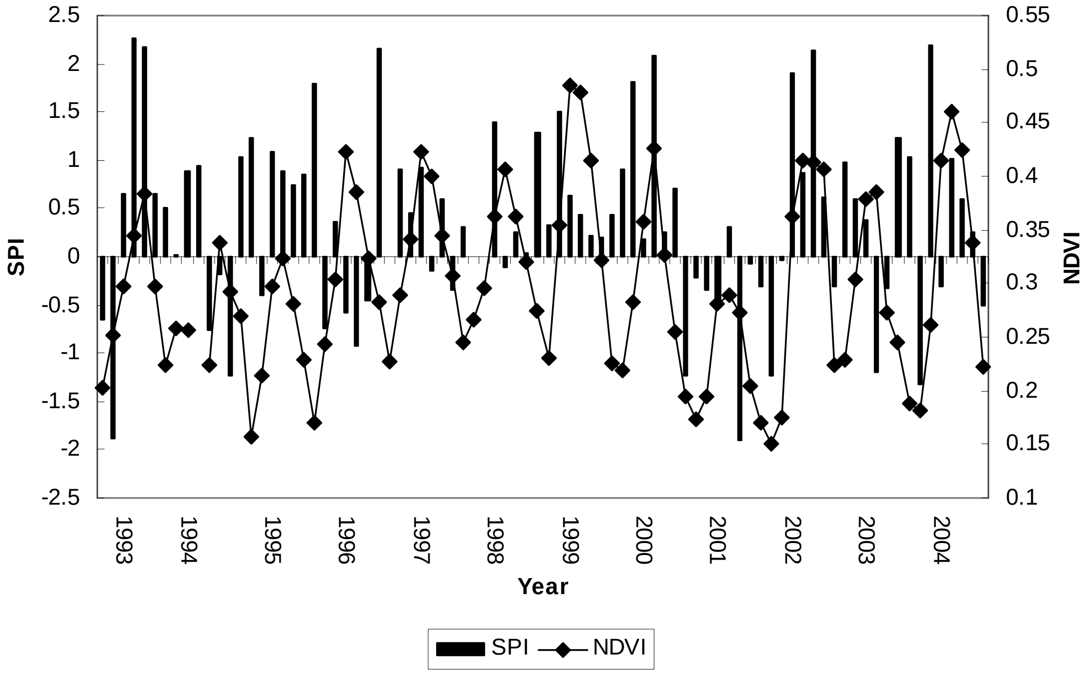

Figure 5.3. 1-month Standardized Precipitation Index (SPI) from April to October. NDVI data for each month are also plotted. NDVI values for April and May, 1994 are contaminated by cloud cover.

for 2000, 2002, and 2004. NDVI values for 1999 are exceptionally high, which will be discussed in a later section. 1993 is an exception due to the severe drought in May, though it had high moisture in July and August. Furthermore, the combination of temperature and precipitation influences the appearance time of the NDVI peak. In 2004, the precipitation amount in May is 131.8 mm (SPI = 2.19). Due to the low temperature in May and June, the appearance of the NDVI peak is between July 11th and July 21st. High soil moisture also makes the growing season last longer. NDVI values drop below 0.25 between October 1st and 11th (e.g, in 2004). Similarly, the high soil moisture in June, July, and August, 1993, causes the appearance of NDVI to peak from August 1st to 11th.

5.6.3 Relationships between precipitation, temperature, and NDVI

There are positive correlations between precipitation, SPI, and NDVI during the full growing season. The correlation coefficient between precipitation for the growing season and mean NDVI is 0.37 ($P > 0.05$). The correlation coefficient increases from 0.37 to 0.59 ($P<0.05$) when SPI is used. Specifically, precipitation in May highly influences NPP in the northern mixed prairie. The correlation coefficient for SPI in May and NDVI in June is 0.67 ($P < 0.05$) which indicates the importance of the amount of precipitation in the early growing season (Bonsal *et al.* 1999). NDVI reaches maximum late if the early growing season (mainly in May) has less precipitation, as in 1993, 1995, and 2003. The highest NDVI peak in 1999 might not only be contributed by the moisture in May, but also the background information of the canopy. As mentioned above, the relatively wet background (caused by the high amount of precipitation) contributes to the high NDVI (Huete *et al.* 1985).

Furthermore, relationships between monthly precipitation, temperature, and NDVI during the growing season can be described using the below equation. About half of the variations in NDVI can be explained by changes in temperature and precipitation which indicates their important influence on vegetation growth. However, other factors, such as topography, species competition, litter accumulation, and chances, also contribute to vegetation growth.

$$NDVI = - 0.04 \times Temperature - 0.005 \times Precipitation + 1.17$$

($R^2 = 0.59$ Adjusted $R^2 = 0.49$)

5.6.4 Temporal heterogeneity

Corresponding to the seasonal variation in precipitation, grassland NPP temporal heterogeneity also showed a yearly variation, with the variation being the highest in the full growing season (Figure 5.4). NPP of the northern mixed prairie shows regular seasonal variation, with a rapid increase before full growing season. Normally the highest variation occurs around June 10th (which may change due to the various combinations of precipitation and temperature). Among all the factors, different emergence time of forb, shrub, and grass species contribute much to the variation in the early growing season. The variation drops slightly during the full growing season after the full growth of dominant grass species. Spatial variation increases again in the late growing season (e g. in August due to the senescence of grass species).

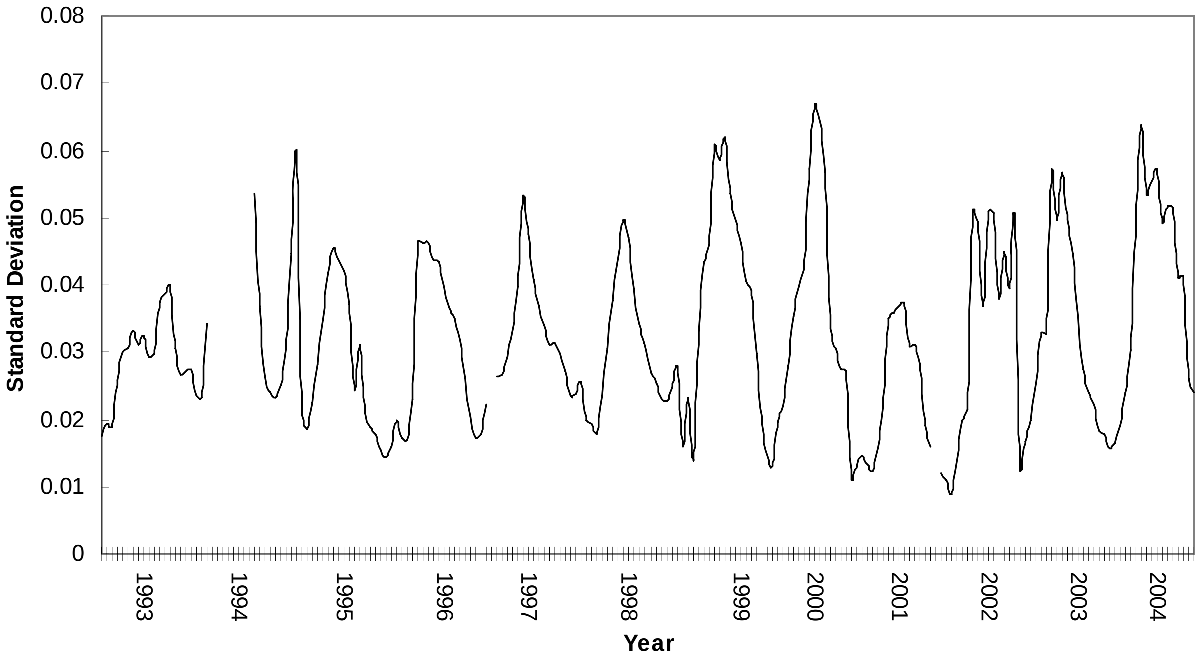

Figure 5.4. Spatial heterogeneity of net primary production for the northern mixed prairie

from 1993 to 2004. No data exists for May and June, 1994 and April, 1997 because of the contamination of the atmospheric condition.

Variation becomes small after the senescence of shrub species. Snow may largely increase the variation, as in October, 1994 (Figure 5.4). The grassland is homogeneous before growing season (as in April) because there is only biological crust and dead material. The situation is the same after the late growing season (as in late September and October) when only senescent materials, dead materials, and biological crust are present. The contrast is the largest between the valley grassland and upland grassland before the full growing season. While shrubs (willow, sagebrush, etc.) flourish with high NDVI, upland areas have lower NDVI value due to their sparse canopy.

Comparing the degree of variation, 1995, 1999, 2000, and 2004 have higher variation and 1993 and 2001 have lower variation with other years in between. This moderately corresponds to the amount of precipitation during the growing season ($r = 0.46$, $P<0.1$). Average yearly spatial heterogeneity is highly correlated with maximum NDVI ($r = 0.79$, $P<0.01$), that is, the higher the NPP, the larger the variation. This is reasonable because the largest contrasts exist when weather conditions are favorable and vegetation is flourishing. Higher NPP appears in places with favorable conditions such as higher soil moisture and organic content, which is the case for shrub communities. Lower NPP corresponds with vegetation communities that have high slopes, low soil moisture, compact soil texture, or low nutrition levels. The contrast between high and low NPP increased when precipitation and temperature were favored for vegetation growth. In places with lower NPP, those unfavorable factors decrease soil moisture under higher than normal precipitation, therefore restricting the increase of vegetation production. There were also large monthly variations for each year, which were most likely the result of precipitation variability. This was the case in 1993, 2002, and 2003. Vegetation growth in the northern mixed prairie responds quickly to precipitation (Sims and Risser 2000). Therefore, it is possible that a large spatial variation happens after a moderate intensity rain.

Generally, there is a trend of increased biological variation from 1993 to 2000. However, biological heterogeneity decreased in 2001 due to a severe drought. Heterogeneity then increased from 2001 to 2004. The increased variation is most likely due to the larger contrast between shrub and grass communities. For example, the drought in 2001 might have a significant influence even on shrub growth, with shrub community's highest NDVI value around 0.4 (compared with 0.7 for a normal year), for 2003 however, the drought did not highly influence the shrub community but did influence the grass community. NDVI values for shrub communities are around 0.6. One anomaly is with the biological heterogeneity in 2003. 2003 was also a drought year, however, it has fairly high variation, which can be explained mainly by drought severity. The drought was not severe enough to influence the growth of shrub communities. Consequently, the contrast between upland and valley grassland is even larger than that for moist 2002.

There is also a significant relationship between SPI and spatial heterogeneity of NPP. Correlation of coefficient between SPI of May and SD of June is 0.82 ($P<0.01$), which compliments previous findings. Precipitation in May not only influences the full growing season production but also the heterogeneity.

5.6.5 Trend of NPP in the GNP

Most pixels in the west block of the Park are relatively stable (-0.006 < slope < 0.006) during this 12-year period though they have annual variation from year to year induced by climatic variation (Figure 5.5). Some pixels, shown with white/light or dark colors, had weak positive or negative trends. The white/light pixels in the centre mainly correspond to bad-lands and valley grassland, with an increasing NPP which can be partly explained by the removal of cattle grazing. Pixels with positive trend along the Park boundary have higher NPP. This may

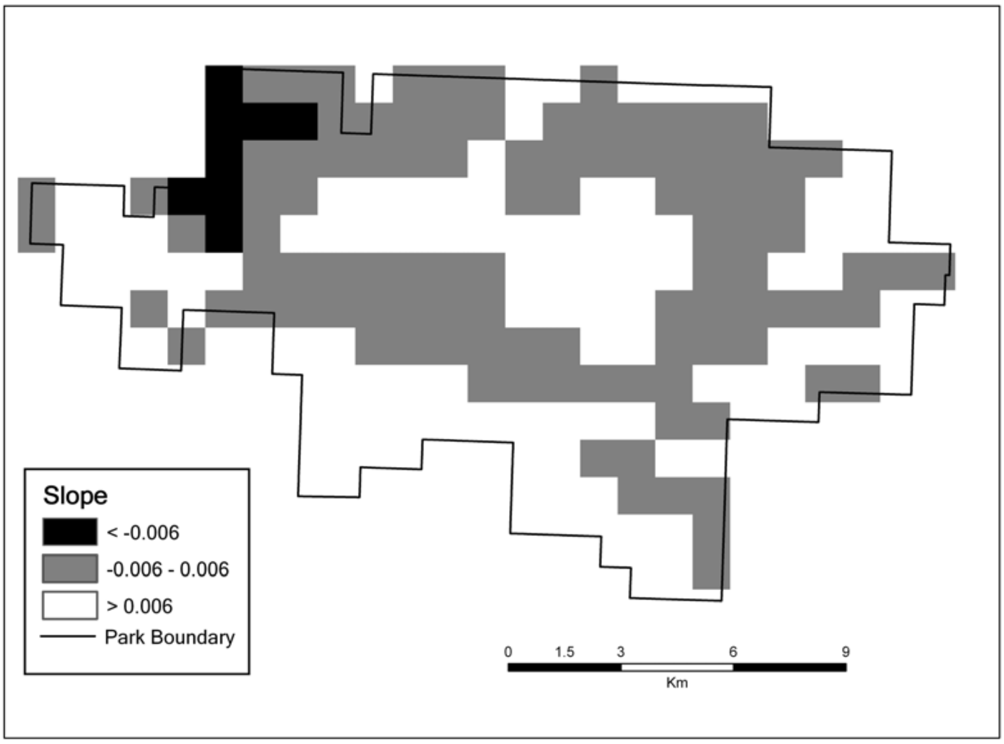

Figure 5.5. Slope image of NDVI MVC from 1993 to 2004 in the west block of the Grassland National Park. A linear regression analysis was applied on the twelve years integrated NDVI for each pixel and slope of the linear regression was shown for the Park area. While dark

color indicates negative trend, white/light color represents positive trend.

be explained by the removal of grazing. Cattle grazing has mostly occurred in flat regions like valley and upland grasslands. With the removal of grazing, the green vegetation is most likely to be kept throughout the growing season and as a result increases the NDVI values. The compact soil texture, low organic soil content, and low soil moisture in most of the bad-lands make the progress of recovery slow. Therefore, the slow progress of dead material accumulation will not influence reflectance or vegetation growth strongly. Of course, the large amount of precipitation in 2002 and 2004 may also contribute to the increase in vegetation cover.

Compared with the positive trends, negative changes are relatively weak. Most of the pixels with negative trends are located in the northwest corner of the Park, chiefly due to the accumulation of dead materials by the removal of cattle grazing. Grazing influences litter accumulation mainly by the consumption of grass production. Trampling by cattle also enhances the rate of decomposition of litter by compacting the litter and increasing contact with the soil (Smoliak *et al.* 1971, Willms *et al.* 1986, Naeth *et al.* 1991, Willms *et al.* 2002). Litter can also influence diversity by changing the habitat of certain grass species through microclimate modification, mainly moisture and temperature (Willms *et al.* 2002). Litter accumulation can block grass growth by slowing the increase in soil temperature during the early growth season (Facelli 1991). For these pixels, even though 2004 was a moist year, the low NDVI value indicates that the precipitation did not help to increase vegetation production. For the whole area, average NPP for 2004 is the highest among the years, except 1999. Therefore, a negative trend probably existed in this area. A few pixels close to, or along the

Frenchman River, also showed a negative trend. This can be explained mainly by the dominance of crested wheatgrass in this area. Based on my observation, the domination of the crested wheatgrass will highly block the growth of other native grass species due to its high competitiveness for nutrition and sunlight. It also increases the speed of dead material accumulation in the semiarid environment due to the removal of cattle grazing. Therefore, the removal of grazing cattle has multiple effects. It can increase vegetation cover in certain areas and help to speed up dead materials accumulation in other areas. Given a longer time, this trend should be much more obvious.

5.7 Discussion

5.7.1 Spectral characteristics of the mixed prairie in Canada

The application of satellite remote sensing in studying vegetation is based on the hypothesis that the phenological change of vegetation has influence on its seasonal reflectance dynamic. Apart from soil nutrition, the cyclic change of soil moisture and soil temperature during the year, controlled by the variation of precipitation and air temperature, are the most important factors contributing to vegetation growth. Therefore, it is vital that climatic data should be used to explain the change in NPP. As mentioned in the previous section, the northern mixed prairie is distinctive for its sparse vegetation cover, biological crust, and large amount of dead material, which has proven to be challenging when applying satellite remote sensing in the study of the cyclical characteristics of vegetation production (Zhang *et al.* 2006). Vegetation canopies with less than complete coverage are especially susceptible to the influence of varying soil and moisture backgrounds (Huete *et al.* 1984, Huete and Warrick 1990, Beck *et al.* 1990). Therefore, the northern mixed prairie shows distinctive spectral characteristics. First, it has high NDVI values (around 0.20-0.23) at the beginning of the growing season, compared with 0.099 from a study in a semiarid grassland in Kenya (Justice *et al.* 1986). Second, it has higher peak NDVI values (0.4-0.5) than other vegetation communities in semiarid environments (e.g. 0.25 to 0.3 for rangeland in semiarid environments (Rigina and Rasmussen 2003)) during the full growing season. Third, it shows several obvious phases of NDVI increase and decrease throughout the year (Figure 5.6). NDVI continually increased from 0 to 0.18 between March 1st and March 20 (Julian date 61 to 80). These increases correspond with the snow melt, with only the daily maximum temperature reaching above 0 ºC. Only dead material and biological crust exists in the grassland at this time due to the low temperature. Dead materials have higher NDVI values than bare soil. Biological crusts show a slight photosynthetic activity and respond to rain (snow melt in this case) rapidly and their NDVI values can reach 0.2 to 0.3 (Karnieli *et al.* 1996, Schmidt and Karnieli 2000). Therefore, it is reasonable to conclude that these high NDVI values before the growing season should be contributed to mainly by the biological crust and dead materials. For the growing season, shrub communities along the Frenchman River have high NDVI values (around 0.6). Consequently, average NDVI values for the park are higher than grasslands in other semiarid environment. As a result, these specific characteristics of the northern mixed prairie make the application of the moving average method to decide the start and end of growing season inappropriate. Therefore, temperature should be considered when deciding green-up time.

It is reasonable to select 0.25 as a threshold value for the mixed prairie (Figure 5.6). In the early growing season, there is a rapid increase from below 0.25 to above 0.25 (Julian day 121 to 131). Some shrub and forb species may start growth before Julian day 121, which can be seen from the slow increase in NDVI. However, only the wide green-up of forb, shrub, and crested wheatgrass can be shown by the rapid increase of NDVI values. Similarly, there is a rapid drop of NDVI values from above 0.25 to below 0.25 in the late growing season. Of course, shrub communities have a different rhythm than grass species with a longer growing season. Some shrub and forb species (e.g. silver sagebrush) may remain green even into early November. NDVI values are still high for shrub communities in late November (>0.4). However, due to their small area in the grassland the green signal does not contribute substantially to the average.

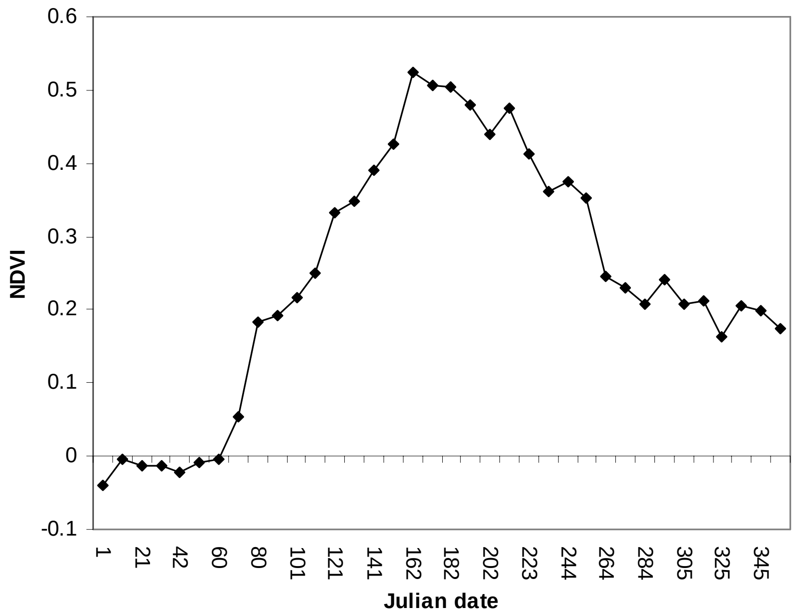

Figure 5.6. Averaged NDVI data for the park area in 1999. NDVI values were low (<0) during the winter due to influences of snow cover.

5.7.2 SPOT VEGETATION and AVHRR NDVI

The consensus of data from two sensors, SPOT Vegetation and AVHRR, is one of my concerns. Fortunately, two datasets have overlap in 1998. Table 5.1 shows the descriptive stats for NDVI values for the park. Generally, two datasets show similar values, with SPOT having higher values for the full growing season and AVHRR having higher values for the early and late growing season. This may be due to SPOT Vegetation's higher radiometric resolution (Duchemin *et al.* 2002).There is about a 7.7% difference for averaged yearly NDVI between SPOT Vegetation NDVI MVC and AVHRR NDVI MVC data. Because we use mean NDVI for the growing season to represent NPP, the average value will minimize the differences between these two sensors. Therefore, it is reliable to use these two datasets together to study historical NPP.

Table 5.1. Comparison of NDVI values from SPOT Vegetation and AVHRR in 1998

		April	May	June	July	August	September	Annual Average
SPOT	Average	0.228	0.242	0.247	0.452	0.382	0.319	0.312
	SD	0.018	0.023	0.032	0.057	0.047	0.031	0.035
	Maximum	0.284	0.344	0.364	0.596	0.503	0.428	0.420
	Minimum	0.188	0.196	0.184	0.307	0.259	0.243	0.229
AVHRR	Average	0.266	0.296	0.363	0.406	0.363	0.321	0.336
	SD	0.020	0.024	0.044	0.051	0.035	0.025	0.033
	Maximum	0.400	0.435	0.588	0.570	0.494	0.481	0.495
	Minimum	0.235	0.267	0.288	0.290	0.296	0.283	0.276

5.7.3 Field validation

Close range hyperspectral data capture almost the same pattern of spectral curve for the growing season (Figure 5.7). Average NDVI values for May, June and July, and August are 0.32, 0.42, and 0.31 respectively, which coincide well with AVHRR and SPOT NDVI data. There are differences between NDVI values from two ways of measurement, which can be explained as yearly variations. It is interesting to see how lichen and moss, --especially moss, --contribute largely to reflectance for the sparse vegetation canopy in the northern mixed grassland. Two quadrats with different grass cover can have the same NDVI value. Moss is one of the main contributors to a high NDVI value for quadrats with very sparse vegetation cover.

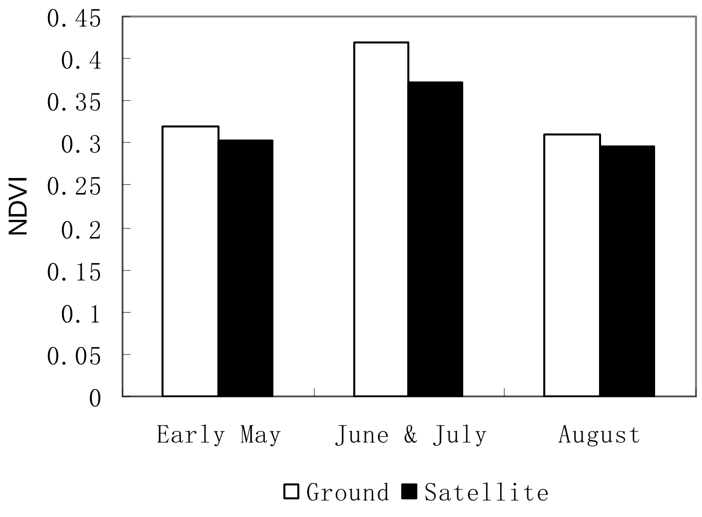

Figure 5.7. Comparison of NDVI values from NDVI MVC and ground hyperspectral measurements for the northern mixed prairie in May, June and July, and August. Ground hyperspectral data were collected with an ASD FR Pro spectroradiometer. There is a good

match between ground collected and satellite based NDVI.

5.8 Conclusions

This study investigated the feasibility of using coarse spatial resolution and high temporal resolution NDVI MVC to study NPP and its variation in the spectrally specific northern mixed prairie. Results indicate that apart from their coarse spatial resolution, AVHRR NDVI MVC and SPOT Vegetation NDVI MVC can show the seasonal and yearly NPP variation, which is highly related to temperature and precipitation. NPP in June is highly correlated with soil moisture in May, with early season precipitation playing an important role in yearly NPP. Furthermore, trend line analysis helps to explore and explain the pattern and variation of NPP in the Park. Results show that most areas in the Park had stable NDVI values during these 12 years of protection, apart from the annual variation. However, some pixels do show negative or positive trends, which can be explained by the accumulation of dead materials and removal of grazing cattle. Therefore, removal of grazing cattle had multiple influences on the grasslands ecosystem, by decreasing NPP in parts of the upland grassland and increasing NPP in the valley grassland. By exploring the temporal heterogeneity of NPP across the Park, it was found that the variation is positively related to the NDVI values and hence the soil moisture condition. Variation reaches its peak right before the full growing season due to the large contrast between shrub and grass communities.

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CHAPTER 6 - SUMMARY

This study applies optical broadband medium resolution multiple-spectral satellite imagery (Landsat and SPOT), RADARSAT-1 imagery, high temporal but low spatial resolution AVHRR and SPOT Vegetation imagery, field collected hyperspectral data, and biophysical data to study the spatial and temporal variation of the northern mixed prairie. Results from this thesis show that it is possible to monitor the heterogeneity in spite of the challenges from the complex vegetation canopy. The study was built on five hypotheses: (1) the measurement of heterogeneity is scale dependent. There should be a scale for measuring variation at community level; (2) the northern mixed grassland is spectrally specific. It is possible to monitor the biological variations within the mixed prairie ecosystem using remote sensing techniques; (3) certain spectral vegetation indices are better than others at extracting biological information for the northern mixed prairie; (4) parameters from texture analysis will provide efficient ways to measure grassland heterogeneity; and (5) high temporal and low spatial resolution imagery will be effective at temporal heterogeneity measurement. The variation can be evaluated through measuring Net Primary Productivity (NPP). All hypotheses have been validated.

6.1 Conclusions

6.1.1 Scales for the study of the northern mixed prairie ranges from 30 m to 124m

Results show that the northern mixed prairie in the park area can be separated into two groups according to topography; (1) upland and sloped grassland dominated by needle-and-thread (*Stipa comata Trin. & Rupr.*) and (2) communities in valley grassland (or in depressions) dominated by western wheatgrass (*Agropyron smithii Rydb.*) and northern wheatgrass (*Agropyron dasystachym*). Differences between these two groups mainly exist in the soil moisture, topography, soil characteristics, and dominant vegetation species. It is hard to separate sloped grasslands from upland grasslands because they are similar in species composition and cover. Furthermore, environmental factors (soil moisture and organic content) moderately influence vegetation growth and the variation of vegetation communities.

There are high correlations between vegetation indices (NDVI, RDVI, ND705, ND680, and NDWI) and biological parameters. These vegetation indices are useful for detecting Plant Area Index (PAI, projected area of all vegetation parts normalized by the subtending ground area), total biomass, and green vegetation cover. A further semivariogram analysis indicates that different scales exist for different parameters. The spatial scales of variation for biological parameters range from 34 m to 120 m, standing dead materials having the largest range. Scales for most vegetation indices (55 and 66 m) are similar to the scales for total biomass and environmental factors. Therefore, it is reliable to use the scale of the spectral vegetation indices to decide the spatial scale of the green vegetation growth. The recommended spatial resolution for the northern mixed prairie can be set as 10 – 20 m to discern the conspicuous biological variations from upland to valley grasslands.

6.1.2 Broad band satellite imagery can be useful in extracting information for northern mixed prairie health

The northern mixed prairie is spectrally specific. Its spectral curve is midway between the spectral curve for bare soil and green healthy vegetation. This phenomenon is mainly caused by its low vegetation cover, large amount of dead material, and biological crust. The sparse canopy resulted in low biomass with an average above ground biomass of 261.0 g/m^2. Dead materials accounted for about 50.0% of total biomass and covered 38.1% of the understory. Moss and lichen are important components of understory biological crust in the northern mixed prairie with 32.7% and 8.6% covers respectively. However, it is still possible to detect the northern mixed prairie by using reflectance from green, red, SWIR, and vegetation indices to extract information on biological parameters. It was found that different vegetation indices are good at detecting different biological parameters and some empirical relationships have been set up between reflectance, vegetation indices, and biological parameters.

6.1.3 Textural parameters can be applied to extract information of variation on the northern mixed prairie

It was found that Radarsat imagery is useful to extract heterogeneity information because it is highly related to soil moisture, the key factor of vegetation growth in the northern mixed prairie. Furthermore, it was noticed that canopy moisture correlated moderately with the variation of Radarsat backscatter, which indicates that vegetation canopy probably contributes to the variation of backscatter. Therefore, one can use textural parameters (e.g., contrast, mean, and correlation) measured from the Radarsat imagery to detect field vegetation variation. Certain parameters, including mean, correlation, dissimilarity, and contrast, could be used to predict heterogeneity of grass biomass, total biomass, and grass cover.

6.1.4 The temporal variation in the northern mixed prairie can be explained by climatic factors

This study highlights the specific cyclic characteristic of the northern mixed prairie. First, it has high NDVI values (around 0.20-0.23) at the beginning of the growing season, compared with 0.099 from another study in a semiarid grassland in Kenya. Second, it has higher peak NDVI values (0.4-0.5) than other vegetation communities in semiarid environments (e.g. 0.25 to 0.3 for rangeland in semiarid environments during the full growing season). Third, it shows several obvious phases of NDVI increase and decrease throughout the year. The finding of the present study also validates that SPI is a useful indicator of soil moisture condition for the northern mixed prairie. It was noted that NPP in June is highly correlated with soil moisture in May, with early season precipitation playing an important role in annual NPP. Furthermore, results of trend line analysis show that most areas in the Park have stable NDVI values during these 12 years of protection, barring from the marginal year to year variation. However, some pixels do show negative or positive trends, which can be explained by the accumulation of dead materials and removal of cattle grazing. Therefore, removal of cattle grazing had multiple influences on the grasslands ecosystem by decreasing NPP in some parts of the upland grassland and increasing NPP in the valley grassland. By exploring the temporal heterogeneity of NPP across the Park, it was found that NPP is positively related to the SPI values and hence the soil moisture condition. Variation reaches its peak right before the full growing season due to the large contrast between shrub and grass communities.

6.2 Possible Applications

6.2.1 Spatial resolution of satellite imagery

The most appropriate resolution should be around 10 – 20 m for the northern mixed prairie if the study objective is to extract the spatial biological variation. As a result, currently available satellite images, SPOT 4 and 5, Radarsat 1 (and Radarsat 2 in the future), and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), are good for the study of variation in the mixed prairie ecosystem. Though Earth-Observing -1 Hyperion and Landsat 5 and 7 have only 30 m resolutions, their hyperspectral characteristics and/or long history archives make them valuable to test their ability to extract biological variation.

6.2.2 Application of Synthetic Aperture RADAR in the study of ecosystem dynamics

The high correlations between biophysical parameters for SPOT image (taken in late June) and low correlation for Landsat image (taken in mid-July) indicate that the optimum time for remote sensing of the mixed prairie is the full growing season for normal year, late June or early July, when the growing period is at its peak for a normal year. However, the cloud cover during the growing season is likely to interfere in capturing images to the desired clarity.

Therefore, it is necessary to apply Synthetic Aperture Radar imagery with different polarizations and viewing angles to study biological changes due to its ability to penetrate through cloud cover and its sensitivity to soil moisture and topography.

6.2.3 Monitoring vegetation ecosystem health dynamics

The change of ranges (spatial autocorrelation) for biological parameters is highly related to the fragmentation of vegetation communities. Therefore, it is possible to monitor changes of the grassland ecosystem by measuring ranges from historically archived remotely sensed images. While increase of ranges indicates a higher spatial autocorrelation and therefore homogenization, decrease of ranges may signify a lower spatial autocorrelation therefore the decrease of community sizes.

6.2.4 Decision making for the schedule of field work and park management strategies

Studying historical changes of NPP in the mixed prairie helps to decide the schedule of field campaign and planning the strategies for management purposes. Generally, shrub and forb species start growing in around mid April. The growth of crested wheatgrass begins as early as the first week of May. Native grasses begin growing in late May. The full growing season arrives in late June and early July for native grass species. Most grass species turn brown from mid to late July in a normal year. However, forb and shrub species may keep green till late October. When deciding the time of field work, influences of temperature and precipitation should be further considered, especially for the early growing season. The full growing season will be late if there is low temperature or large amount of precipitation for May. Therefore, the timing of field campaign should be decided both by research objectives and prevailing climatic conditions. Results of trend and temporal heterogeneity analyses should also be useful for adjusting and manipulating the management strategies such as delimiting the areas for cattle grazing. Such management plans will ensure the recovery of the biodiversity as a certain intensity of grazing is necessary to reduce the dead materials accumulation.

6.3 Limitations

This study discussed the efficiency of heterogeneity measurement and possibility of detecting the northern mixed prairie. However, there are still gray areas that need to be addressed in future studies:

(1) Lack of validation due to the lack of cloud free satellite imagery during the field season for two years

The field work was done during three consecutive years (2003-2005). However, only two images were collected during the field campaign in 2005 due to the influences of cloud cover. Therefore, changes from 2003 to 2005 could not be detected and the relationships between biological parameters, vegetation indices and textural parameters could not be validated.

(2) The problem of scale

The sample interval of the field work is 10 m with each sample an area of 0.25 m^2. However, the IFOVs (or pixel spacing) of satellite imagery range from 12.5 to 30 m. This tended to spur a discrepancy when the field data were correlated with satellite images. This discrepancy might probably explain why there are no significant correlations between biological parameters, textural measurements, and Geary's C and Getis's G* statistic (data not shown) on the 2005 SPOT image (One exception is that the variation of standing dead materials is negatively correlated with homogeneity ($r = -0.63$, $P<0.01$), which is reasonable because the canopy reflectance is highly influenced by dead materials). Of course other factors including the mixed information in pixels contribute to the low correlation. However, a further test of influences of scales should be conducted.

(3) Lack of satellite hyperspectral data

It is obvious that the ground collected hyperspectral data are useful at detecting biological variation. However, only multispectral data were used for correlation analysis due to the lack of satellite hyperspectral data, which might be the main hindrance of extracting pure vegetation information from each pixel. It seems likely that the application of satellite hyperspectral data will highly improve the efficiency of monitoring the northern mixed prairie.

APPENDIX

FIELD DATA COLLECTION FORM (Transects)

Quadrat								
Location								
Grass								
Forb								
Shrub								
Standing dead								
Litter								
Moss								
Lichen								
Rock								
Bareground								
Average height								
Slope								
Litter depth								
Needle-and-thread								
Western wheatgrass								
Blue grama								
June grass								
Pasture sage								
Sage brush								
Cactus								
Biomass (g)								
Soil Core (g)								

Note:

FIELD DATA COLLECTION FORM (Plot description)

Plot Description

Date	**Time**		**Site**	**Plot**
				Recorder

	Easting	**Northing**	**Elevation**	**Accuracy**
GPS				

Slope: flat / low slope ($<3^0$) / moderate slope (3^0-10^0) / high slope ($>10^0$)

Aspect:

Community: Needle&grama / Needle&grama with sage / Porcupine with sage

Dominant species not in quadrats (walk in the plot for 10 minutes):

Location description (e.g., soil moisture condition, other specific features)

NOTES:

Soil core (g)					
C0					
E1		**E3**		**E5**	
W1		**W3**		**W5**	
N1		**N3**		**N5**	
S1		**S3**		**S5**	

Biomass (g)					
C0					
E1		**E3**		**E5**	
W1		**W3**		**W5**	
N1		**N3**		**N5**	
S1		**S3**		**S5**	

FIELD DATA COLLECTION FORM (Plots)

Date: **Time:** **Recorder:**

2005 Fieldwork Form -- Site

Plot Series:		**Rel. elev.:**			**Easting:**			**Northing:**			
Quadrat	**Series**										
	Slope										
	Aspect										
Cover-top layer	**Grass**										
	Forb										
	Shrub										
	Standing dead										
Cover-Low layer	**Litter**										
	Moss										
	Lichen										
	Rock										
	Bare ground										
Height	**Litter depth**										
	Average height										
	No. of hits: 0-10										
	10-20										
	20-30										
	30-40										
	40-50										
Cover of grass species	**Needle-and-thread**										
	Western wheatgrass										
	Slender wheatgrass										
	Northern wheatgrass										
	Blue grama										
	June grass										
	Pasture sage										
	Sage brush										
	Cactus										
	Unidentified grasses										
Soil moisture											
Soil temperature											
Biomass											

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SELECTED PUBLICATIONS

Zhang C., X. Guo, J. Wilmshurst, S. Crump, and D. Hildebrand Monitoring Temporal Heterogeneity in a Protected Mixed Grassland Ecosystem Using 10-day NDVI Composite (Prairie Forum, accepted with minor revisions)

Zhang, C. and X. Guo. Monitoring Northern Mixed Grassland Health Using Broadband Satellite Imagery. (International Journal of Remote Sensing, accepted pending revisions)

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CONFERENCE PRESENTATIONS

Zhang, C., X. Guo, J. Wilmshurst, S. Crump, and D. Hildebrand. Monitoring NPP Trend in a Protected Mixed Grassland Ecosystem Using NDVI 10-day Composite Data. Soil & Crop 2006, Saskatoon, SK**,** Canada

Zhang, C., X. Guo, and J. Wilmshurst Measuring Grassland Heterogeneity with Hyperspectral Remote Sensing Products. 2005 Annual Meeting of Canadian Association of Geographers, London, ON, Canada

Zhang, C., X. Guo, J. Wilmshurst, and R. Sissons. Application of Radarsat Imagery on Grassland heterogeneity Assessment. Soil & Crop 2005, Saskatoon, SK, Canada

Zhang, C., X. Guo, J. Wilmshurst, and R. Sissons. The Evaluation of Broadband Vegetation Indices on Monitoring Northern Mixed Grassland. 2004 Annual Meeting of Prairie division of the Canadian Association of Geographers, Muenster, SK, Canada

Zhang, C. and X. Guo. Forb Abundance Detection in Northern Mixed Grass Prairies Using Remote Sensing Techniques. Soil & Crop 2004, Saskatoon, SK, Canada

Zhang, C. and X. Guo. Impacts of Protection on Northern Mixed Grassland Biophysical Characteristics. 2003 Annual Meeting of Prairie Division of the Canadian Association of Geographers, Gimili, MB, Canada

RESEARCH PROJECTS

2003 – Present Measuring Grassland Heterogeneity: A Multispatial, Multitemporal, and Multispectral Approach

2004 Measuring Grassland Structure for Recovery of Grassland Species at Risk

2001-2002 Eco-system Carrying Capacity of Karst Region in Guangxi Province

1996-2000 Environmental Migration and Its Impacts on Natural Environment in Karst Regions, Guangxi Province

1998-1999 Agricultural Expert Decision Supporting System in 4-lake Area

1997-1999 Sustainable Development of Wuling Region

HONORS AND AWARDS

06 / 2005 The Best Ph.D. Student Paper Presentation
GISicence Study Group, the Canadian Association of Geographers, Canada

06 / 2005 Travel Award
The Canadian Association of Geographers, Canada

06 / 2005 Travel Award
University of Saskatchewan, Canada

06 / 2005 President Fund for Traveling
University of Saskatchewan, Canada

09 / 2004 Student Paper Award
Prairie Division of the Canadian Association of Geographers, Canada

09 / 2003 Student Paper Award
Prairie Division of the Canadian Association of Geographers, Canada

09 / 2003 Travel Award
University of Saskatchewan, Canada

09 / 2002 - 08 / 2005 Graduate Teaching Fellowship
University of Saskatchewan, Canada

ASSOCIATION MEMBERSHIPS

- The Association of American Geographers (AAG)
- The Canadian Association of Geographers (CAG)
- The Institute of Electrical and Electronics Engineers (IEEE)